Impacts on passengers and operators of service reliability for the case of a multi-level public transit network

Aaron Lee
Impacts on passengers and operators of service reliability for the case of a multi-level public transit network

Master of Science Thesis

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

Aaron Lee

August 26, 2013

Faculty of Civil Engineering and Geosciences (CEG) · Delft University of Technology
Committee

Prof.dr.ir. Bart van Arem
Dr.ir. Rob van Nes
Dr. Jan Anne Annema
Dr.ir. Niels van Oort
Abstract

A framework is developed to calculate reliability from the passengers perspective in a multi-level public transit network. The major variables that impact reliability for transfers passengers are identified as: scheduled transfer time, headways of connecting lines, variation of vehicle operations, transfer walking time and proportion of transferring passengers. These variables are examined in the context of changing the scheduled transfer time in a hypothetical network and in the case that a holding strategy is added at the transfer point. It is shown that a trade-off exists between scheduled transfer time and reliability. Holding at a transfer point can be beneficial to passengers transferring to the held line, depending on the scheduled transfer time. The calculation method is applied to a cost-benefit analysis to a small example using data from the tram network in The Hague, Netherlands. Benefits to passengers are quantified from changes to the magnitude of a passenger’s travel time, including scheduled travel time and additional travel time, as well as the width of the travel time distribution using the reliability ratio as a value for reliability. Although it is difficult to set a schedule that benefits different groups of transferring passengers, it is possible to realize travel time and reliability benefits through scheduling.
Executive Summary

Have you ever missed a connection between public transit vehicles and watched the tail end of your desired vehicle disappear into the sunset? Is your public transit commute unpredictable, as in, does it seem to take a different amount of time every day? When traveling by public transit, do you choose to depart earlier than you would like to because there is a chance that your trip will take more time than advertised? Your public transit network might be experiencing problems with reliability. Don’t worry. It is fairly common among public transit networks around the world. But how reliable (or unreliable) is your public transit trip of choice and, more importantly, how much can it be improved?

Service reliability in transit operations is gaining increasing attention from transit operators and researchers. Passengers benefit from increased reliability in the form of decreased and more predictable travel times, while operators can benefit with lower costs and potential for increased ridership. For passengers, arriving when planned has been shown to be among the most important attributes of a transit service, additional waiting and in-vehicle time have been shown to have a higher disutility than expected waiting and in-vehicle time, and reliability has been shown to be a factor in both route choice and mode choice.

Reliability improvements can be made at the strategic (network design), tactical (schedule design) and operational levels as detailed in the PhD thesis by Van Oort (2011). While his work was done for a single transit line, a logical next step is an extension of this work to include transferring passengers in the calculation framework, and to study the effect of transfer synchronization on reliability. In the Netherlands 28% of national rail passengers continue their journey by some other form of public transportation, so the attention to transferring passengers is warranted.

The main objectives of this thesis are (1) to extend the additional travel time calculation model in Van Oort (2011) to account for passengers traveling through a transfer point, (2) to test two tactical reliability improvement measures in a network situation and identify the impacts on the various passenger groups and (3) to identify the costs and benefits for each operator associated with these improvement measures. A fourth objective is intertwined with the previous three: the understanding of the main variables that affect reliability at a transfer point.

Two reliability improvement measures that are tested: transfer synchronization and vehicle holding. The effects of these measures are examined in the context of several passenger groups,
including transferring passengers for each specific transfer, and direct passengers who do not transfer. Automatic Vehicle Locator (AVL) and passenger data from the tram operator in The Hague, Netherlands is used to demonstrate a small example of how this method can be applied to a cost-benefit analysis.

Quantification of reliability for transferring passengers

Service reliability from a passenger’s perspective is based on the passengers actual travel times. A route with consistent travel times, as compared to the schedule, would be considered as reliable, while a route with a greater variation among travel times would be considered as less reliable, because there is a greater chance that the passenger will arrive outside of their preferred time range. Passenger reliability indicators are used to quantify results, including the magnitude of reliability effects on passengers: Additional Travel Time (ATT) and the distribution of from reliability effects on passengers Reliability Buffer Time (RBT). These indicators are shown in Figure 1.

![Figure 1: Additional travel time indicates the average additional time due to unreliability. Reliability Buffer Time indicates the width of the distribution of actual travel times. Adapted from Van Oort (2011)](image)

Calculations for passenger reliability at a transfer point depend heavily on the process of the transfer. Actual travel time experienced by passengers are broken into 4 groups: passengers that make their first and second vehicle (as intended), passengers that make their first vehicle but miss their second, passengers that miss their first vehicle and make their second and passengers that miss both vehicles. The calculation is done slightly differently for each of these groups, an example for the case of long headways on both services is shown in Figure 2.

The process of the transfer also leads to the identification of the major variables that impact reliability at a transfer. These are: the distribution of arrival and departure times of vehicles on both lines, the amount and distribution of transfer walking times, the headways of the vehicles on both lines, the number of passengers on a specific transfer and the scheduled transfer time. These variables all impact the probability that passengers will make or miss their connection, which essentially determines travel time distributions.

Reliability and synchronization

A simulation of a hypothetical network is used to test the impacts of scheduled transfer time and holding on reliability. This hypothetical network is the intersection of one tram line, traveling in both directions and one train line, with traffic in both directions. This essentially leads to 4 different “lines” and a total of 8 possible transfers. A passenger pattern
and schedule are assigned to the network. Actual vehicle arrival and departure times are taken from a normal distribution. The main difference between the tram and train lines is that the train was not allowed to depart early from any of the stops on its line.

In order to examine the 5 important variables, several tests are run with this model. The scheduled transfer time is varied for all transfers in the network. Some transfers are dependent on one another, for example varying a transfer, has an opposite effect on the opposite transfer. For passengers traveling through a single transfer it is shown that reliability increases with greater scheduled transfer times, however a trade off exists between the transfers that cannot be varied independently. This is shown for the case of long headways in Figure 3.

The standard deviation of the distribution of vehicle arrival and departure times is also varied. This is shown to have an effect on the scheduled transfer time. In general, smaller variations of vehicle operations lead to more reliable transfers at shorter scheduled transfer times.

Tests were done for both short and long (10 and 15 minute) headways. As expected, the longer headway has a bigger effect on the consequence of an unreliable service. Passengers experience more additional travel time, on average, for a longer headway because the consequence of missing a transfer is greater.
Another important trade-off is between scheduled transfer time and reliability. In general, an increase in scheduled transfer time leads to a gain in reliability. When the reliability gains are greater than the costs of increased scheduled time, then a change becomes valueable. Figure 4 shows an example of this for a single transfer. The graph represents the sum of scheduled transfer time, additional transfer time and reliability buffer time. An optimal point can be reached for this transfer with minimum cost to passengers. However, varying one transfer leads to an inevitable variation of another transfer, so the average scheduled transfer time does not have as much of an effect when multiple transfers are considered together.

![Figure 4: Sum of additional travel time for all groups of transferring passengers](image)

**Holding for transferring passengers**

Adding a holding point is a measure that can be used to diminish the size of the distribution of vehicle times. Traditionally, a holding point introduces a trade off between passengers downstream of the holding point who benefit from the reduced vehicle departure distributions and passengers traveling through the holding point who accrue additional travel time from waiting inside vehicles that are held. When the holding point is located at a transfer, transferring passengers add a new dimension to this trade off. It is shown that for shorter scheduled transfer times, holding has a net benefit for transfer passengers, but for longer scheduled transfer times, holding creates a net loss. This is shown for the case of long headways in Figure 5.

**Cost-benefit analysis for example case**

AVL and passenger flow data from the tram line 9 in Den Haag, Netherlands is used as input for the calculation model. Here it is shown that, even in a grossly simplified situation (there are several tram lines and a train line at the station that are excluded from analysis), the trade-offs of reliability improvements between passenger groups are very complex in this situation. The schedule of the tram line was varied to show the possible reliability under different scheduled transfer times. One optimal location was idenfied and the differences in (1) scheduled travel time, (2) additional travel time and (3) standard deviation of travel times

Aaron Lee

Master of Science Thesis
were used to show the cost and benefits to different passenger groups and the whole network in the case of shifting the tram schedule. Standard deviation of travel times was used as an indicator of the width of the distribution instead of reliability buffer time in order to be consistent with the current value of reliability practice in the Netherlands.

The results of the benefits and costs to different passenger groups are shown in Table 1. While this improvement in this case is net-beneficial (depending on a more realistic operator cost estimate), one real takeaway from this is that in optimizing a transfer for reliability, certain passenger groups are favored, while others are neglected.

40% of the passenger benefits can be attributed to the change in the standard deviation, or width of the distribution. This confirms that a change in reliability can have a significant impact on passenger benefits.

<table>
<thead>
<tr>
<th>Passengers</th>
<th>Scheduled</th>
<th>ATT</th>
<th>STDev</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transfer G</td>
<td>89.2</td>
<td>€-163.58</td>
<td>€138.74</td>
<td>€47.01</td>
</tr>
<tr>
<td>Transfer I</td>
<td>89.2</td>
<td>€59.48</td>
<td>€0.01</td>
<td>€0.00</td>
</tr>
<tr>
<td>Transfer J</td>
<td>29.6</td>
<td>€-19.71</td>
<td>€0.26</td>
<td>€0.49</td>
</tr>
<tr>
<td>Transfer L</td>
<td>29.6</td>
<td>€54.21</td>
<td>€-2.54</td>
<td>€-3.60</td>
</tr>
<tr>
<td>Total (2hr)</td>
<td></td>
<td>€-69.60</td>
<td>€136.48</td>
<td>€43.90</td>
</tr>
</tbody>
</table>

Table 1: Change in benefits to passengers for the small example case

Conclusions

The main contributions of this thesis are a method that is used to calculate reliability for transferring passengers, the existence of a trade-off between scheduled travel time and reliability, the interdependency of multiple transfers involving the same line and the impact that reliability can have on a cost-benefit analysis.

Insights into the impacts of reliability at a transfer point are gained by splitting passengers into specific groups and splitting passengers travel costs into scheduled time, additional travel time and reliability buffer time. Policy decisions will vary from situation to situation, but
with this method it is clear which passengers benefit, which passengers do not benefit and the impact of increased reliability on those benefits.

Transit operators should begin to consider reliability from a passengers perspective and work this into their schedule planning. If there is room to shift schedules, it is possible to create benefit for passengers, which in turn could increase transit ridership. Governments should consider passenger reliability in their assessments of public transit projects, however further research needs to be done the effect of reliability on passenger behavior.
Table of Contents

1 Introduction 1
1.1 Problem .................................................. 1
1.1.1 What is Reliability? .................................. 1
1.1.2 Why is reliability important? ....................... 3
1.1.3 Importance of the transfer ......................... 4
1.2 Scope ..................................................... 4
1.3 Research Objectives ..................................... 5
1.4 Research Question ....................................... 6
1.5 Framework and Document Outline ..................... 6

2 Reliability of a Public Transit Transfer Point 9
2.1 Causes of and solutions for unreliability ........ 9
2.1.1 Causes of variability and unreliability .......... 10
2.1.2 Improvement measures ............................... 10
2.2 Reliability Indicators ................................... 10
2.2.1 Historical Indicators (operationally based) .... 11
2.2.2 Current indicators (passenger based) .......... 11
2.3 The effect of transfers on reliability ............... 12
2.3.1 Conclusions from reliability of transfers ....... 13
2.4 Improvement measures used in this thesis ......... 14
2.4.1 Schedule Coordination or Synchronization .... 14
2.4.2 Holding Points ....................................... 15
2.4.3 Conclusions from Reliability Improvement Measures ... 16
2.5 Literature Review Conclusions ...................... 16

3 Costs and Benefits to Passengers and Operators 19
3.1 Values of changes ....................................... 19
3.1.1 Reliability indicators .............................. 19
3.1.2 Type of studies ...................................... 20
3.1.3 Approaches to the valuation of reliability .... 20
3.2 Costs of changes ........................................ 22
<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.3</td>
<td>Effects of changes to reliability on passengers and operators</td>
<td>22</td>
</tr>
<tr>
<td>3.4</td>
<td>CBA Framework</td>
<td>24</td>
</tr>
<tr>
<td>3.5</td>
<td>Conclusions from Costs and Benefits</td>
<td>24</td>
</tr>
<tr>
<td>4</td>
<td>Calculations and Variables of Reliability for Transferring Passengers</td>
<td>27</td>
</tr>
<tr>
<td>4.1</td>
<td>Travel Time Components</td>
<td>27</td>
</tr>
<tr>
<td>4.2</td>
<td>Passenger Groups</td>
<td>28</td>
</tr>
<tr>
<td>4.2.1</td>
<td>Travel time variability for through passengers</td>
<td>29</td>
</tr>
<tr>
<td>4.2.2</td>
<td>Travel time variability for transferring passengers</td>
<td>29</td>
</tr>
<tr>
<td>4.2.3</td>
<td>Passenger perspective</td>
<td>30</td>
</tr>
<tr>
<td>4.3</td>
<td>Calculation Framework</td>
<td>30</td>
</tr>
<tr>
<td>4.3.1</td>
<td>Additional Waiting Time: for direct passengers</td>
<td>32</td>
</tr>
<tr>
<td>4.3.2</td>
<td>Additional In-Vehicle Travel Time</td>
<td>33</td>
</tr>
<tr>
<td>4.3.3</td>
<td>Additional transfer time: for transferring passengers</td>
<td>34</td>
</tr>
<tr>
<td>4.3.4</td>
<td>Additional Travel Time for passenger groups and the network</td>
<td>37</td>
</tr>
<tr>
<td>4.4</td>
<td>Reliability buffer time for transfer passengers</td>
<td>40</td>
</tr>
<tr>
<td>4.5</td>
<td>Variables leading to travel time variation</td>
<td>40</td>
</tr>
<tr>
<td>4.5.1</td>
<td>Scheduled transfer time</td>
<td>40</td>
</tr>
<tr>
<td>4.5.2</td>
<td>Headways</td>
<td>41</td>
</tr>
<tr>
<td>4.5.3</td>
<td>Variation of vehicle arrival and departure times</td>
<td>42</td>
</tr>
<tr>
<td>4.5.4</td>
<td>Transfer walking time</td>
<td>43</td>
</tr>
<tr>
<td>4.5.5</td>
<td>Proportion of Transferring passengers</td>
<td>44</td>
</tr>
<tr>
<td>4.6</td>
<td>Conclusions from Calculations and Variables</td>
<td>44</td>
</tr>
<tr>
<td>5</td>
<td>Network and Input Data</td>
<td>45</td>
</tr>
<tr>
<td>5.1</td>
<td>The Hypothetical Network</td>
<td>46</td>
</tr>
<tr>
<td>5.1.1</td>
<td>Passenger Flows</td>
<td>46</td>
</tr>
<tr>
<td>5.1.2</td>
<td>Scheduled and Actual arrival and departure times</td>
<td>48</td>
</tr>
<tr>
<td>5.1.3</td>
<td>Parameters for hypothetical network</td>
<td>50</td>
</tr>
<tr>
<td>5.2</td>
<td>Input data for the real network</td>
<td>50</td>
</tr>
<tr>
<td>5.2.1</td>
<td>Vehicle Departure and Arrival Times</td>
<td>50</td>
</tr>
<tr>
<td>5.2.2</td>
<td>Passenger Assignment</td>
<td>52</td>
</tr>
<tr>
<td>5.3</td>
<td>Networks and Data: Conclusions</td>
<td>53</td>
</tr>
<tr>
<td>6</td>
<td>The Five Major Variables tested in a Hypothetical Network</td>
<td>55</td>
</tr>
<tr>
<td>6.1</td>
<td>Scheduled Transfer Time</td>
<td>56</td>
</tr>
<tr>
<td>6.1.1</td>
<td>Scheduled transfer time for short headways</td>
<td>56</td>
</tr>
<tr>
<td>6.1.2</td>
<td>Scheduled transfer time for long headways</td>
<td>58</td>
</tr>
<tr>
<td>6.2</td>
<td>Headways</td>
<td>58</td>
</tr>
<tr>
<td>6.3</td>
<td>Variation of Vehicle Arrivals and Departures</td>
<td>62</td>
</tr>
<tr>
<td>6.3.1</td>
<td>Standard deviation of the first line</td>
<td>62</td>
</tr>
<tr>
<td>6.3.2</td>
<td>Standard deviation of the second line</td>
<td>64</td>
</tr>
<tr>
<td>6.3.3</td>
<td>Conclusions of variation of vehicle operations</td>
<td>64</td>
</tr>
<tr>
<td>6.4</td>
<td>Number of Passengers</td>
<td>64</td>
</tr>
<tr>
<td>6.5</td>
<td>Transfer Walking Time</td>
<td>65</td>
</tr>
<tr>
<td>6.6</td>
<td>Reliability and Scheduled Travel Time</td>
<td>65</td>
</tr>
<tr>
<td>6.7</td>
<td>Conclusions and Overview of Results</td>
<td>66</td>
</tr>
</tbody>
</table>
# Table of Contents

7 Effects of Holding on Transfer Passengers 69

7.1 Effect of holding at the transfer point ............................................. 69

7.1.1 Effect of holding for short headways ............................................. 70

7.1.2 Effect of holding for long headways ............................................. 70

7.2 Holding Point Location ................................................................. 74

7.2.1 Impact on transfers to the line with holding ................................. 74

7.2.2 Impact on transfer from the line with holding ............................... 75

7.3 Conclusions from holding at a transfer point .................................... 75

8 Application to Real Data and Cost Benefit Analysis 77

8.1 Analysis of Results ...................................................................... 78

8.1.1 Current characteristics of the case ............................................ 78

8.1.2 Regularization of headways at transfer point .............................. 79

8.1.3 Shifting of the tram schedule .................................................... 80

8.1.4 Conclusion of analysis ........................................................... 80

8.2 Cost-Benefit Analysis .................................................................. 83

8.2.1 Benefits and costs to passenger groups ................................... 83

8.2.2 Costs to Operators ................................................................. 84

8.2.3 Cost-Benefit Ratio ................................................................. 85

8.3 Conclusions for real data example ............................................... 85

9 Conclusion and Recommendations 87

9.1 Takeaways for transit operators, governments, transportation professionals and laypeople ......................................................... 89

9.2 Recommendations for further research ........................................ 90

A Comparison of similar transfers .................................................. 91

B Scheduled Time and Reliability Long Headways 93

C Sensitivity analysis for number of passengers in CBA case 95

D Cost Benefit Analyses ................................................................. 97
List of Figures

1 Additional travel time indicates the average additional time due to unreliability. Reliability Buffer Time indicates the width of the distribution of actual travel times. Adapted from Van Oort (2011) ........................................ iv
2 Additional travel time indicates the average additional time due to unreliability. Reliability Buffer Time indicates the width of the distribution of actual travel times. Adapted from Van Oort (2011) ........................................ v
3 Sum of additional travel time for all groups of transferring passengers ............. v
4 Sum of additional travel time for all groups of transferring passengers ........... vi
5 The difference in average additional travel time of a holding point for the affected passenger groups and the whole system in long headways conditions ........ vii
1.1 Early or late departures will affect on-time performance for the remainder of the route. Adapted from Van Oort (2011) ................................. 2
1.2 Variability increases with line length. Adapted from Van Oort (2011) .......... 3
1.3 The interaction between the main objectives of this thesis ..................... 5
1.4 Framework and reading guide for this thesis ................................. 7
2.1 Additional travel time indicates the average additional time due to unreliability. Reliability Buffer Time indicates the width of the distribution of actual travel times. Adapted from Van Oort (2011) ........................................ 11
2.2 A holding point is applied with the intention to reduced the variability of vehicle departures at, and downstream from that point ................... 15
3.1 The scheduling approach (Small, 1982) ........................................ 21
3.2 The main costs and benefits to each passenger group and to both the tram and train operators .................................................. 23
3.3 Example cost-benefit analysis with the impacts of reliability .................. 25
4.1 The travel time components that are considered in the calculation of reliability metrics ................................................................. 28
4.2 The six passenger groups and their routes through a transfer point ............ 28
4.3 Various scenarios that lead to additional travel time ............................ 30
<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.4</td>
<td>The framework used for the calculation of additional travel time and reliability buffer time depending on the network characteristics and passenger types</td>
</tr>
<tr>
<td>4.5</td>
<td>Additional waiting time at the initial stop</td>
</tr>
<tr>
<td>4.6</td>
<td>Stochastic elements of a passenger transfer</td>
</tr>
<tr>
<td>4.7</td>
<td>Visual of additional transfer time for the case of transferring from a short to long (and long to long) headway</td>
</tr>
<tr>
<td>4.8</td>
<td>Visual of additional transfer time for the case of transferring from a long to short headway</td>
</tr>
<tr>
<td>4.9</td>
<td>The amount of scheduled transfer time has an impact on the amount of passengers that make or miss a connection</td>
</tr>
<tr>
<td>4.10</td>
<td>The headway of the second vehicle has an impact on the amount of additional travel time experienced by passengers that miss their connection</td>
</tr>
<tr>
<td>4.11</td>
<td>The standard deviation of arrival times of the first vehicle has an effect on whether or not a passenger makes their connection</td>
</tr>
<tr>
<td>4.12</td>
<td>The standard deviation of arrival times of the first vehicle has an effect on whether or not a passenger makes their connection</td>
</tr>
<tr>
<td>4.13</td>
<td>The amount or distribution of walking time has an effect on weather or not a passenger makes or misses their connection</td>
</tr>
<tr>
<td>5.1</td>
<td>The hypothetical network used for initial calculations. The dashed line represents the tram line and the solid line represents the train line</td>
</tr>
<tr>
<td>5.2</td>
<td>Boardings of different passenger groups for the hypothetical tram line</td>
</tr>
<tr>
<td>5.3</td>
<td>A graphic indicating the direction of each transfer. For the rest of this thesis, passenger groups will be represented by symbols, so that it is clear when a certain passenger group is included in an analysis</td>
</tr>
<tr>
<td>6.1</td>
<td>Additional travel time and reliability buffer time for passengers traveling through Transfer A, a train-to-tram transfer</td>
</tr>
<tr>
<td>6.2</td>
<td>Additional travel time and reliability buffer time for passengers traveling through Transfer D, a tram-to-train transfer</td>
</tr>
<tr>
<td>6.3</td>
<td>Comparison of additional travel time and reliability buffer time all transfer passengers</td>
</tr>
<tr>
<td>6.4</td>
<td>Additional travel time and reliability buffer time for passengers traveling through Transfer A, a train-to-tram transfer</td>
</tr>
<tr>
<td>6.5</td>
<td>Additional travel time and reliability buffer time for passengers traveling through Transfer D, a tram-to-train transfer</td>
</tr>
<tr>
<td>6.6</td>
<td>Comparison of additional travel time and reliability buffer time all transfer passengers</td>
</tr>
<tr>
<td>6.7</td>
<td>Average additional travel time for transfer specific passengers for three different headways (top) and the relation of average additional travel time to headway of the second vehicle (bottom)</td>
</tr>
<tr>
<td>6.8</td>
<td>The effect of varying the standard deviation of a tram line and a train line for transfers from tram-to-train and train-to-tram</td>
</tr>
<tr>
<td>6.9</td>
<td>The effect of passenger numbers while varying the schedule of both tram lines, thus varying the scheduled transfer times of all 8 transfers for maximum impact</td>
</tr>
<tr>
<td>6.10</td>
<td>Combination of scheduled travel time and reliability for Transfer A with short headways</td>
</tr>
<tr>
<td>6.11</td>
<td>Combination of scheduled travel time and reliability for Transfer D with short headways</td>
</tr>
</tbody>
</table>
7.1 The effect of a holding point on passengers transferring from Train to Tram for a unique transfer (Transfer A), while varying the scheduled transfer time ........................................ 71
7.2 The difference in average additional travel time of a holding point for the affected passenger groups and the whole system .............................................................. 71
7.3 Contributions from passenger groups affected by holding to the change in system wide average additional travel time ........................................................................ 72
7.4 The effect of a holding point on passengers transferring from Train to Tram for a unique transfer (Transfer A), while varying the scheduled transfer time, in long headway conditions ................................................................. 72
7.5 The difference in average additional travel time of a holding point for the affected passenger groups and the whole system in long headways conditions .............. 73
7.6 Contributions from passenger groups affected by holding to the change in system wide average additional travel time for long headway conditions ....................... 73
7.7 Holding point location and it’s effect on difference in additional travel time for passengers transferring to a line with holding ................................................................. 74
7.8 For tight transfers (2 minutes in this case), a holding point applied before the transfer point causes an increase in additional travel time ........................................... 75
8.1 The effects on single transfer passenger groups of shifting the line 1 direction of Tram line 9 in Den Haag .................................................................................... 81
8.2 The effects on single transfer passenger groups of shifting the line 2 direction of Tram line 9 in Den Haag .................................................................................... 82
A.1 Comparison of additional travel time and reliability buffer time for the 4 transfers from train-to-tram ......................................................................................... 91
A.2 Comparison of additional travel time and reliability buffer time for the 4 transfers from tram-to-train ......................................................................................... 91
B.1 Combination of scheduled travel time and reliability for Transfer A with long headways .............................................................................................................. 93
B.2 Combination of scheduled travel time and reliability for Transfer D with long headways .............................................................................................................. 94
B.3 Combination of scheduled travel time and reliability for all transfer passengers with long headways .............................................................................................. 94
C.1 Sensitivity of number of transfer passengers for all transfers while shifting the schedule of Tram direction 1 ..................................................................................... 96
C.2 Sensitivity of number of transfer passengers for all transfers while shifting the schedule of Tram direction 2 ..................................................................................... 96
D.1 Travel time costs and benefits, using reliability buffer time ........................................................................................................................... 98
D.2 The framework used for the calculation of additional travel time and reliability buffer time depending on the network characteristics and passenger types .... 99
List of Tables

<table>
<thead>
<tr>
<th>Table</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Change in benefits to passengers for the small example case</td>
<td>vii</td>
</tr>
<tr>
<td>2.1</td>
<td>Selected literature regarding reliability of transfers</td>
<td>12</td>
</tr>
<tr>
<td>4.5</td>
<td>Extension of the additional transfer time calculations for the case of transferring from a short to long headway or a long to long headway</td>
<td>37</td>
</tr>
<tr>
<td>4.6</td>
<td>Extension of the additional transfer time calculations for the case of transferring from a long to short headway</td>
<td>38</td>
</tr>
<tr>
<td>4.9</td>
<td>The causes and effects of the 5 important variables for reliability at a transfer</td>
<td>41</td>
</tr>
<tr>
<td>5.1</td>
<td>Numbering of lines and their relation to the network diagram</td>
<td>46</td>
</tr>
<tr>
<td>5.2</td>
<td>Percent of tram passengers in each passenger group for the hypothetical network. Pictures of the passenger groups are found in Figure 5.3</td>
<td>48</td>
</tr>
<tr>
<td>5.4</td>
<td>Parameters for network used in varying the number of passengers</td>
<td>51</td>
</tr>
<tr>
<td>5.6</td>
<td>Parameters for varying the standard deviation on the tram line 2</td>
<td>52</td>
</tr>
<tr>
<td>6.1</td>
<td>The five main variables with a new results column, showing the results of calculations in a hypothetical network</td>
<td>68</td>
</tr>
<tr>
<td>8.1</td>
<td>Deviation characteristics of the lines in the test case</td>
<td>78</td>
</tr>
<tr>
<td>8.2</td>
<td>Additional travel time and reliability buffer time for each transfer in the current evening schedule on line 9</td>
<td>79</td>
</tr>
<tr>
<td>8.3</td>
<td>Original and new schedule, designed for uniform headways at the Transfer Point (Den Haag HS)</td>
<td>79</td>
</tr>
<tr>
<td>8.4</td>
<td>Additional travel time and reliability buffer time for each transfer in the current evening schedule on line 9</td>
<td>80</td>
</tr>
<tr>
<td>8.5</td>
<td>Changes in scheduled travel time (STT) and reliability (in minutes) for impacted passengers</td>
<td>83</td>
</tr>
<tr>
<td>8.6</td>
<td>Change in travel time and reliability benefits to passengers</td>
<td>83</td>
</tr>
<tr>
<td>8.7</td>
<td>Process times for the evening tram schedule on line 9 in Den Haag for the current case and the new case where the schedule of the line 1 direction is shifted</td>
<td>84</td>
</tr>
<tr>
<td>8.8</td>
<td>Operating costs for a two-hour period</td>
<td>84</td>
</tr>
<tr>
<td>8.9</td>
<td>Benefit-cost ratios for the example case</td>
<td>85</td>
</tr>
</tbody>
</table>
Have you ever missed a connection between public transit vehicles and watched the tail end of your desired vehicle disappear into the sunset? Is your public transit commute unpredictable, as in, does it seem to take a different amount of time every day? When traveling by public transit, do you choose to depart earlier than you would like to because there is a chance that your trip will take more time than advertised? Your public transit network might be experiencing problems with reliability. Don’t worry. It is fairly common among public transit networks around the world. But how reliable (or unreliable) is your public transit trip of choice and, more importantly, how much can it be improved?

This thesis intends to analyze the potential for improvement in service reliability for the case of a multi-level public transit network. The focus will be on the effects of reliability improvement measures at a tactical level on the different passenger groups and different operators. Reliability will be considered from a passenger perspective and will be measured using average additional travel time (ATT) per passenger and reliability buffer time (RBT). This expands upon similar work done for the case of a single transit line by Van Oort (2011), by considering the case of a network and accounting for passenger transfers between lines.

This thesis calculates reliability for transfer passengers based on actual data in a method that can be used by transit operators with access to simple automatic data collection, including vehicle arrival and departure times, and passenger boardings and alightings. Transit operators can use this method to assess their reliability performance, or to predict the changes in reliability due to a service change by simulating a future case.

This method is used to examine the reliability improvement potential of synchronization of transfers and holding at a transfer point in a hypothetical network. Then the method is applied to real data from the tram operator (HTM) in The Hague, Netherlands in order to show its application to cost-benefit analysis.

1.1 Problem

1.1.1 What is Reliability?

Reliability is generally understood, but widely defined as it relates to public transit operations. It is defined by Levinson (2005) as “where transit vehicles run on-time and adhere to schedules,” by Van Oort et al. (2012) as “the match of planning and operations”, and by
Abkowitz et al. (1978) as “the invariability of service attributes which influence the decisions of travelers and transportation providers.” Levinson’s definition is limited to the characteristics of vehicle operation, while Abkowitz et al. (1978) indicates that the level of reliability is related to the passenger. From a purely operational perspective, reliability is related to the timeliness of vehicles, whereas the level of reliability from a passenger perspective relates to the variation of a passengers actual travel time when compared to scheduled travel time. Abkowitz’s definition is the best fit for this research, particularly because of the language about the influence of passenger and operator decisions.

Van Oort (2011) shows that reliability from a passenger perspective (“demand side”) is related to the reliability of vehicle operations (“supply side”). It follows that the level of reliability depends on the variability of the system. Variability can originate from a number of factors that can be categorized into two main groupings: terminal time departure variability and vehicle trip time variability (Van Oort, 2011). For the former, an early or late departure from the terminal will result in an early or late arrival at each stop (Figure 1.1). Vehicle trip time variability includes all variations in trip times that are caused by the variable causes along the route, including other traffic and driver behavior. This variability increases as a vehicle moves further along its line as shown in Figure 1.2 (Nelson and O’Neil, 2000; Veiseth et al., 2007). The actual arrival time at any point along the line is distributed around a mean arrival time with some vehicles arriving early and some vehicles arriving late. A more reliable service will have less variability in this distribution leading to a more predictable service pattern and travel times.

![Figure 1.1](image.png)

**Figure 1.1**: Early or late departures will affect on-time performance for the remainder of the route. Adapted from Van Oort (2011)
1.1.2 Why is reliability important?

Service reliability is important to both passengers and operators. Passengers benefit from a reliable transit system that gets them to their desired destination at the expected time. Operators benefit from a reliable network, as an increase in reliability can lead to a decrease in service costs. An unreliable network results in unpredictability for the traveler and unnecessary expenditures for the operator.

For passengers an unreliable transit service can increase passenger waiting time (Wilson et al., 1992), can reduce the probability of an on-time arrival at a passenger’s destination (Abkowitz et al., 1978), can result in additional travel time, and can reduce the probability of finding a seat (Van Oort, 2011).

Because of the potential for negative effects, it is not surprising that passengers place considerable importance on reliability. A study of consumer preferences for public transportation ranked “arriving when planned” as the most important attribute of a transit service, closely followed by “having a seat” (Golob et al., 1972). Balcombe et al. (2004), summarize several studies and conclude that additional waiting time and additional in-vehicle time due to unreliability have a higher disutility than expected waiting time and in-vehicle time. A stated preference research by König and Axhausen (2002) concludes that reliability is a factor in a travelers route choice. Several studies have shown that a travelers route and mode choice may be affected by unreliability (Turnquist and Bowman, 1980; Schmöcker and Bell, 2002).

Public transit operators have been monitoring reliability for over 100 years (Levinson, 2005). Initially, the most important factors to operators included schedule adherence and passenger loads (Levinson, 2005). Abkowitz et al. (1978) write that reliability from a bus operators perspective is treated as an operational consideration, stressing the importance of adherence to schedules.

An improvement in reliability can affect both revenues and costs (Abkowitz et al., 1978). From an operational perspective, an unreliable network means a higher chance of having to dispatch additional vehicles or drivers (leading to increased operating costs) and the higher
costs of a less efficient schedule (Abkowitz et al., 1978). The higher level of service due to increased reliability can attract new passengers and increase revenues.

1.1.3 Importance of the transfer

The transfer point plays an important role in reliability for transferring passengers because it provides an opportunity to increase the variation in a passenger’s trip. Mai et al. (2012) show that a passenger’s journey through a transfer point can have a significant variation due to the possibility that one or both vehicles can be missed. Ceder et al. (2013) conclude that passengers prefer a transfer scenario that has a lower variability of out-of-vehicle time.

In the Netherlands 28% of national rail passengers continue their journey by some other form of public transportation (Savelberg and Bakker, 2010). The public transit operator in the Hague (HTM) is required to maintain a certain level of connection of the national rail network (NS) in their concession agreement. This highlights the importance of extending Van Oort (2011) to consider the reliability of transfers.

1.2 Scope

The possibility for study in this field is rather large, so this thesis will require some scoping. This will be done in terms of the type of variability, the types of improvement measures considered, the type of network and the indicators.

As in Van Oort (2011), this study will be limited to daily, recurring variability and will not consider non-recurring delays and variability that imply unavailability of infrastructure.

This thesis will focus on schedule development for optimal reliability. This leads to a focus on tactical measures, if considering the framework in Van Oort (2011). Strategic measures at the network design level, such as line length and terminal design (Van Oort, 2011), are left out. Operational measures are left out for the same reason as in Van Oort (2011): there is already significant work done in this area, including the implementation of exclusive lanes, traffic lights and synchronization (citations in Van Oort (2011, pg. 110)). Schedule determination will include scheduling transfer times (interactions between lines) and the implementation of holding points.

This thesis will examine the case of a network with the interaction of two bidirectional lines meeting at a transfer station. Two of these lines will be urban transit lines, while two will be intercity rail lines. Although considering a multi-level network skips the step of a simple urban tram network, once this network is set up, the framework can be applied to the case of a single-level network, simply by changing the attributes of each line to reflect an urban transit line. Because of this, the method used to analyze the case of a multi-level network will be applicable in other network cases.

The primary indicator to be used will be additional travel time (Van Oort, 2011) as the intention is to study reliability from a passenger perspective. This indicator will generally be presented as average additional travel time per passenger, to represent the level of reliability of the network. Reliability Buffer Time will also be calculated as it gives an idea of the amount of variation. Traditional indicators, such as punctuality, may be used to illustrate the value of Additional Travel Time.
1.3 Research Objectives

There are three main research objectives for this thesis. The first is to extend the additional travel time calculation model in Van Oort (2011) to account for passengers traveling through a transfer point. The second is to test some tactical reliability improvement measures in a network situation and identify the impacts on the various passenger groups. The third is to identify the costs and benefits for each operator associated with these improvement measures.

![Diagram](image)

**Figure 1.3:** The interaction between the main objectives of this thesis

**Extend Van Oort (2011) reliability calculations to include transfers**

Additional travel time in Van Oort (2011) was considered as a function of additional waiting time and additional in-vehicle time. The transfer adds a new, and important, dimension to this calculation, which changes the calculation for several cases.

The method of using vehicle location data and passenger counts is particularly suited towards an assessment of the current reliability of a system, but can also be used to simulate the impacts of a future change in service.

**Identify impacts of reliability improvements: Scheduled Transfer Time and Holding**

In a multi-level, multi-operator transit network, different passenger groups can be identified. An improvement to one part of the network may positively affect the reliability for one passenger group, while negatively affecting another. This impact will be measured with Additional....
Travel Time and Reliability Buffer Time.

Because a shifting the scheduled transfer time also shifts the scheduled travel time for passengers traveling through a transfer, a trade-off exists between reliability and travel time.

**Costs and benefits to passengers and operators**

If changes are made to a transit network that counts on the interaction of multiple actors, it is likely that these operators will not experience uneven costs and benefits. Costs and benefits will be analyzed for the whole system, as well as for the different passenger groups that travel through a transfer point.

**Identify the major factors that influence reliability at a transfer**

A final objective is to identify the major factors that influence reliability at a transfer. These major factors should be accounted for in the calculation process and their effects should be evident in the results for the reliability improvement measures and the cost-benefit analysis.

**1.4 Research Question**

The research question is:

To what extent can the passenger reliability of a public transit transfer be improved, in a cost-effective way, through tactical measures?

The subquestions are:

1. What are the factors that affect reliability for transferring passengers?
2. What is the impact of the scheduled transfer time on reliability for transfer passengers?
3. What are the impacts and trade-offs for reliability when a holding strategy is applied?
4. How does a change in reliability of a multi-level network impact the costs and benefits to passengers and operators?

**1.5 Framework and Document Outline**

The framework and outline for the rest of this document is shown in Figure 1.4. The document is divided up into three parts: Background, Methods and Results. Each chapter is listed with a brief summary of its intentions. The objectives, as listed above, are shown to the right of this list, and are linked to the chapters in which they are covered.

Background is included in Chapters 1, 2 and 3. Chapters 1 and 2 provide some background for reliability and transfers, while Chapter 3 shows how reliability can be incorporated into cost-benefit analysis. Chapter 4 details the methods for the calculations used for additional travel time and reliability buffer time. The networks used for the calculations are explained in Chapter 5. Chapters 6 through 8 are results chapters. Chapter 6 deals with the main variables of reliability at a transfer, with particular attention to scheduled transfer time. Chapter 7 deals with the implementation of a holding point. In Chapter 8, the method is tested on a small set of real data which results in an example cost-benefit analysis.
Figure 1.4: Framework and reading guide for this thesis
This chapter presents the background literature that is relevant to the primary areas of this thesis. Because the focus is on improvements to reliability of public transit at a transfer point, background must be provided on reliability of public transportation as well as public transit transfers.

This section answers the questions: What are the causes of unreliability and how can a public transit service be made more reliable (Section 2.1)? How is reliability measured for public transit passengers (Section 2.2)? and What effect do transfers have on reliability (Section 2.3)? Finally, Section 2.4 discusses the literature relevant to the improvement measures that are tested in this thesis, synchronization and holding.

This information is presented so that the reader can gain an understanding of the main concepts in this thesis and an understanding of how this thesis is positioned among current literature.

2.1 Causes of and solutions for unreliability

This thesis is intended to build upon the work in Van Oort (2011). Van Oort’s work studies the effect on reliability of five measures, that can be taken at the strategic and tactical level of transit planning. At the strategic level those measures are: Terminal Design, Coordination and Line Length. At the tactical level those measures are: Trip Time Determination and Vehicle Holding. Significant previous work had been done concerning reliability improvements at the operational level (See Van Oort (2011, pg. 110)).

The majority of test cases presented in current research are limited to considering the reliability for the case of a single transit line (Uniman et al., 2010; Van Oort, 2011). Van Oort (2011) notes that the consideration of reliability for the case of a network of lines is an appropriate next step. Chen et al. (2009) claims to analyze reliability at a stop, line and network level, but the metrics used focus on punctuality and regularity of vehicles and do not account for travelers moving through the network or the interaction between lines.
2.1.1 Causes of variability and unreliability

The main causes of service variability can be grouped into internal and external causes. These internal and external causes have effects on both of the main types of variability: terminal departure time (Figure 1.1) and trip time variability (Figure 1.2).

External causes include weather, other traffic, irregular passenger loads and traveler behavior. Internal causes include: schedule quality, driver behavior, infrastructure design, service network design and other public transport.

2.1.2 Improvement measures

The framework in Van Oort (2011) divides reliability improvement measures into three categories: strategic, tactical and operational.

The strategic category encompasses all reliability improvements that can be made through network design. This includes both infrastructure changes and service network changes.

Van Oort (2011) studied terminal design (infrastructure), line length and line coordination (service network). In addition to these, there are several other network design measures that can increase reliability, including: exclusive lanes, stop design, and traffic light priority at the infrastructure level and stop spacing at the service network level.

The tactical category encompasses the reliability improvement measures that deal specifically with timetable design. The measures studied in Van Oort (2011) are: trip time determination and vehicle holding. Both of these measures deal with the allocation of slack in the timetable.

Operational improvement measures are those that can improve reliability during daily operations. Examples of operational measures include: skipping stops (Koffman, 1978; Li et al., 1995; Eberlein et al., 1998), deadheading (Eberlein et al., 1998), headway control, speeding up or slowing down, detours, short turning, adding vehicles and vehicle holding.

Many of these operational measures are connected to actions that must be taken at the strategic or tactical planning stages. For example, detours and short turning require the infrastructure to allow them. Van Oort (2011) argues that vehicle holding depends on the type of schedule (loose or tight) and should be considered at the tactical stage for optimal results.

Van Oort (2011) mentions that synchronization of lines is both a strategic and tactical measure. The decision of which lines to synchronize is perhaps a strategic measure, whereas the choice of schedule is tactical. Synchronization is chosen as an improvement measure to analyze in this thesis because it requires a network approach and was thus not discussed in Van Oort’s single line analysis.

2.2 Reliability Indicators

The wide variety in definitions of reliability leads to a variety of indicators that have been used to represent reliability over time. Historically, indicators were based on operations with little attention paid to the actual effects on passengers. Currently, there is an increase in studies that consider reliability from the perspective of explicitly passenger based indicators.
2.2.1 Historical Indicators (operationally based)

Traditional reliability indicators relate to vehicle punctuality and regularity. Punctuality indicates the adherence to scheduled departure times and is often measured as the percent of departures with an acceptable bandwidth. Regularity is a measurement of the variability of headways between vehicles. One example of a regularity measure is the coefficient of variation of the headway. There are several problems with the traditional indicators as outlined in Van Oort (2011, pg. 37). These indicators focus primarily on the vehicle and not on the passenger. No distinction is made between stops with a high demand and stops with a low demand. The passengers are not affected if a vehicle is off schedule at a stop with no intended boardings. Finally, punctuality and reliability do not quantify the impact of variability on passengers.

2.2.2 Current indicators (passenger based)

Van Oort’s work is centered around the passenger perspective and develops a new, passenger-related, indicator: Additional Travel Time. This is defined as the difference between the average observed travel time and the scheduled travel time (Figure 2.1).

\[ T_{add} = \text{average travel time} - \text{scheduled travel time} \]

\[ RBT = \text{95th percentile of travel time} - \text{average travel time} \]

Figure 2.1: Additional travel time indicates the average additional time due to unreliability. Reliability Buffer Time indicates the width of the distribution of actual travel times. Adapted from Van Oort (2011)

Another indicator intended to measure reliability from the point of view of the passenger is Reliability Buffer Time (Furth and Muller, 2006; Uniman et al., 2010). RBT indicates how much time travelers have to budget in order to account for the variability of actual travel times. In Furth and Muller (2006) and Uniman et al. (2010), the 95th percentile value of travel time is used to calculate this. While Additional Travel Time shows the average amount of extra time for a passenger’s journey over the planned travel time, Reliability Buffer Time demonstrates the variation among travel times. If a passenger wants to guarantee an on-time arrival for the same trip every day, they must add the Reliability Buffer Time as well as Additional Travel Time to their expectation of total travel time.

Using the 95th percentile for Reliability Buffer Time gives an indication of the travel time that one should expect in order to arrive on time in 19 out of 20 repetitions of the same trip. For regular commuters, this equates to a late arrival once per month, which is assumed as acceptable by Furth and Muller (2006).
### Table 2.1: Selected literature regarding reliability of transfers

<table>
<thead>
<tr>
<th>Author (Date)</th>
<th>Vehicle running time</th>
<th>Passenger arrival pattern</th>
<th>Variables</th>
<th>Indicators</th>
</tr>
</thead>
<tbody>
<tr>
<td>Turnquist and Bowman (1980)</td>
<td>Gamma distribution</td>
<td>-</td>
<td>Network shape, Frequency, Demand</td>
<td>2x arrival time deviation plus transfer deviation × number of transfers</td>
</tr>
<tr>
<td>Abkowitz et al. (1987)</td>
<td>Normal</td>
<td>-</td>
<td>Type of schedule, Headway, Demand, Route length</td>
<td>Average transfer time</td>
</tr>
<tr>
<td>Knoppers and Muller (1995)</td>
<td>Normal</td>
<td>-</td>
<td>-</td>
<td>Average transfer time (weighted)</td>
</tr>
<tr>
<td>Ting and Schonfeld (2005)</td>
<td>Normal</td>
<td>Random</td>
<td>Type of holding, scheduled transfer time</td>
<td>Transfer waiting time</td>
</tr>
<tr>
<td>Furth and Muller (2009)</td>
<td>Normal</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Sivakumaran et al. (2012)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>Generalized cost</td>
</tr>
</tbody>
</table>

#### 2.3 The effect of transfers on reliability

Several studies have been done surrounding the topic of reliability in network. Many of these studies use vehicle centered reliability indicators, or focus on more general indicators such as total system cost. The following literature, summarized in Table 2.1, was chosen because it demonstrates the common vehicle arrival distributions, passenger arrival patterns, important variables and indicators that are used when studying the effects of the transfer on passengers.

Turnquist and Bowman (1980) analyzed the effects of network structure on reliability with a simulation approach, and found a greater uncertainty of delay in radial networks than in grid networks. The reliability metric used was coefficient of variation of transfer delays. A gamma distribution was used for bus travel times, based on analysis of bus travel times in Chicago.

Abkowitz et al. (1987) write about the feasibility of timed transfer in transit systems. Four strategies are tested: transfers are not scheduled, transfers are scheduled but buses do not wait for each other, the bus with the longer headway waits and the bus that arrives first waits. Buses were dispatched based on scheduled headways and running time was a function of distance and was normally distributed and passenger volume was assumed to be equal. They identify the preferred strategy depending on headway compatibility and route length.
2.3 The effect of transfers on reliability

Chowdhury and Chien (2002) examine transfers between trains and buses. Their model allows bus-to-bus, bus-to-train and train-to-bus connections. Trains are given a deterministic arrival pattern, while buses are given a stochastic arrival pattern. A numerical search algorithm is used to determine which services to coordinate by finding the set of coordinated services in a trunk-and-feeder network that lead to the minimum total cost.

Chowdhury and Chien (2002) also show that the optimal slack time (transfer time) is a trade-off between transfer time, additional transfer time (if pickup vehicle is late) and missed connection time (if pickup vehicle is missed). The amount of optimal slack time increases with the standard deviation of arrival time, until the point where the standard deviation is too high to warrant coordination.

Passenger demand is inelastic in Chowdhury and Chien (2002), and they recommend to extend their model to be able to properly address fare policy or system objectives involving consumer surplus.

Ting and Schonfeld (2005) writes about the timed transfer in the context of a multiple hub transit network. A heuristic algorithm is used to optimize headways and slack times. Headways are integer multiples of a base pattern. They concluded that schedule coordination is not worth attempting for routes with a high standard deviation of arrivals. Coordination with integer headways is preferable, when some headways are relatively large.

Muller and Furth (2009) present an analytical method for optimizing the transfer buffer time for the minimum transfer waiting time. A long buffer time reduces the probability of missing a transfer, but increases waiting time. A short buffer time decreases waiting time, but increases the possibility of missing the transfer (which increases total waiting time). This optimal point is also found in the cases of holding vehicles at this point, attuned departure control (where the departing vehicle waits until a transfer is possible, but may depart early) and delaying the departure of connecting vehicle, where a vehicle may be held until after its departure time to ensure the connection. This paper used theoretical arrival and departure time distributions.

Mai et al. (2012) show the travel time impact of missed connections with a simulation model of two separate trips containing transfers. Automatic data collected from buses was used for bus travel times. Passenger arrival time was based on Bowman and Turnquist (1981) for a 15 minute headway. Values were sampled for bus departure times and the same data point was used for departure from the origin and departure from the transfer point (due to correlations in this data). Reliability is measured by standard deviation.

2.3.1 Conclusions from reliability of transfers

The above articles can be used to validate the choices made for vehicle and passenger arrival times and to position this work in the context of previous work.

A common trend of the literature is to use a normal distribution when simulating tram and bus running times. This is not necessarily perfectly accurate, but appears to be considered as adequate. The normal distribution is fine to use in an example because it is easily understood and simulates the main idea that urban public transit vehicles tend to run around the scheduled time but are often either ahead or behind.

The common indicators seen in theses studies are generalized cost components, transfer time or simply total travel time, but there is a lack of study of a transfer in the context of passenger reliability.

The way transfers in this thesis are considered is similar to Muller and Furth (2009) in that
the objective is to optimize transfer time. However, the objective here is extended to optimize the reliability of transfers. The method is similar to Mai et al. (2012) in that a simulation method is used to break passengers into four categories depending on whether they make or miss their first and second vehicles. However, Mai et al. (2012) explicitly look at the travel times of each of those four categories, while here the intention is to look at the effects of reliability improvement measures on transferring and non-transferring passengers.

Chowdhury and Chien (2002) use an analytic method to determine which group of transfers to optimize. While the method in this thesis could be used for a similar goal, it differs several ways. The transfer cost function in Chowdhury and Chien (2002) only looks at the average transfer time, while reliability buffer time is used here to give an indication of the width of the distribution. The analytic method is aimed at predicting results based on generic characteristics, while the simulation method used in this thesis gives results based on analysis of operational data. The method in this work is positioned in a way that it can be used as an ex-post evaluation tool. As an analytic method, Chowdhury and Chien (2002) is designed to show the impact on total cost. While the passenger groups going through different transfers are accounted for in the total, the effects on individual groups are not distinguished. The method in this thesis allows for a clear determination of the passenger groups that gain and lose from a change in service.

2.4 Improvement measures used in this thesis

The two reliability improvement measures that are tested in this thesis are: schedule coordination and holding. This section outlines some pertinent background of these two measures.

2.4.1 Schedule Coordination or Synchronization

Schedule Coordination is the concept of setting the arrival schedule of one line and the departure schedule of the next line so that passengers can seamlessly transfer from one vehicle to the other with minimal waiting time. Effective intermodal coordination can increase the attractiveness and productivity of a multi-modal system (Hickey, 1992). The most important variable in schedule coordination is the scheduled transfer time. Here a trade-off exists between the probability of making a connection and increased scheduled travel time (Muller and Furth, 2009). Although a short scheduled transfer time decreases scheduled travel time, it also leads to an increased probability of missing the transfer. Coordination is beneficial for long headways, low standard deviations of arrivals and large transfer demands (Chowdhury and Chien, 2002).

Knoppers and Muller (1995) found that coordination was worthwhile if the standard deviation of the punctuality of the feeder line at the transfer point is less than 40% of the headway on the connecting line. This is in line with work by Lee and Schonfeld (1991) who found coordination not worth attempting when standard deviations of arrivals exceed certain levels. Chowdhury and Chien (2002) showed that as standard deviation increases, benefits from coordination decrease. Ting and Schonfeld (2005) used a heuristic algorithm to optimize headways and slack times with similar results.

Coordination is most beneficial when the headways of both lines are integer multiples of each other (Chowdhury and Chien, 2002; Sivakumaran et al., 2012). Sivakumaran et al. (2012) used a trunk and feeder system and eliminated user waiting time at the transfer point by coordinating feeder vehicles so that they were at integer multiples of the trunk frequency. It was found that coordination can lead to a pareto optimum, such that costs diminish for all
2.4 Improvement measures used in this thesis

2.4.2 Holding Points

Holding Points

A holding point is a stop along a line where a vehicle will be held, if it is ahead of schedule. This reduces the downstream variability, but causes some extra in-vehicle time for those passengers traveling across the holding point.

![Diagram of vehicle time variation with and without holding points.](image)

**Figure 2.2:** A holding point is applied with the intention to reduced the variability of vehicle departures at, and downstream from that point.

While holding is technically an operational measure, its effectiveness depends on how it is implemented into the schedule (Van Oort, 2011).

Holding strategies can be grouped into two categories: schedule based or headway based (Van Oort, 2011). Schedule based holding is related to adherence to the schedule. In this case a vehicle will be held if it is ahead of its scheduled departure at the holding point. Headway based holding is related to the actual headway between vehicles on the line. Here a vehicle will be held if the headway in front of it becomes too small. Schedule based holding is appropriate for the case of long headways, while either method can be used in the case of short headways.

For headway based holding, the holding factor determines how long vehicles are held. A holding factor of 100% means that all vehicles are held until the scheduled headway is achieved. A lower factor means vehicles should be held for a smaller proportion of the time needed to reach the scheduled headway.

For schedule based holding, a maximum holding time can be applied. Vehicles that are ahead of schedule are not held for longer than this maximum, even if they still must depart early.

A maximum holding time can designate a maximum amount of time that a vehicle can be held regardless of the extent of the deviation between the actual and scheduled headways. Generally holding times of longer than 60 seconds are not acceptable to passengers and drivers (Van Oort, 2011).
Optimal Number of Holding Points

In the case of long headways, Furth and Muller (2009) and Van Oort et al. (2012) note that the benefits increase with the number of holding points. However, this increase is very small after the second holding point. An increasing benefit in reliability is shown for the first two holding points used on a line. The benefit of each additional holding point, above 2, is relatively small. Furth and Muller (2009) make this case using total cost and Van Oort et al. (2012) make this case using Additional Travel Time.

Optimal Location of Holding Points

Because of the trade-off associated with holding points, the optimal location of a holding point depends on the passenger pattern on the line. A holding point is beneficial to downstream passengers, so a holding point is most effective when located prior to a large amount of downstream passengers (Turnquist and Bowman, 1980; Abkowitz and Engelstein, 1984; Cats et al., 2011). A holding point is not beneficial for passengers traveling through the holding point, as additional time will be accrued as they wait in the vehicle at the holding point. An effective holding point from this standpoint is one that has a low amount of through passengers (Hickman, 2001; Van Oort, 2011).

2.4.3 Conclusions from Reliability Improvement Measures

The main takeaways from the literature about the selected reliability improvement measures are as follows.

Coordinating transfer schedules is beneficial where there is a low standard deviation of vehicle arrival times, or a greater chance of the connection being assured. Coordinating vehicles is the most beneficial when headways of each line are an integer multiple of each other. The benefit from coordinating schedules comes from reduced waiting time for passengers.

Holding points are beneficial with high amount of downstream boarding passengers and a low amount of through passengers. The benefit of holding comes from a reduction in variation of vehicle arrival and departure times. However there is a travel time cost for passengers that must travel through the holding point.

2.5 Literature Review Conclusions

This chapter has served to position this work in the context of other literature and to summarize the previous literature related to transfers (the primary context of this work), synchronization and holding points (the primary reliability improvement measures in this work).

To summarize:

1. Reliability in public transit networks can be improved in a number of ways, including day to day operational measures, tactical scheduling measures and strategic long term network and infrastructure design measures.

2. The impact of unreliability on passengers is essentially the distribution of passenger travel times. The difference between the mean of this distribution and scheduled travel time (Additional Travel Time), as well as the width of this distribution (Reliability Buffer Time) can combine to describe the reliability of a network for passengers.
3. The main impact of a transfer is the possibility for passengers to miss their transfer, causing them to wait for the next vehicle.

4. Schedule coordination can be beneficial for passengers and operators, if certain conditions are met: integer multiples of headways and a standard deviation of actual times of less than 40% of the running time.

5. A holding scheme involves a tradeoff between the benefit to downstream passengers and the disbenefit to passengers traveling through the holding point.

The key points of this section regarding transfers are used in the development of the calculations for additional travel time for transferring passengers in Chapter 4. Synchronization is tested in a hypothetical network in Chapter 6. There the main factors that affect synchronization are demonstrated and it is shown that it is straightforward to choose a synchronization time for a single transfer, but more complex as more transfers are included.

Schedule based holding is tested with particular attention to transferring passengers in Chapter 7.
Chapter 3

Costs and Benefits to Passengers and Operators

This chapter explains the costs and benefits of changes in reliability for passengers and operators. Changes can be made to reliability by the improvement measures outlined in Chapter 2 and can be measured by the passenger reliability metrics: additional travel time and reliability buffer time. These changes will, of course, have an impact on passengers and operators. Section 3.1 explains the current theory behind representing the value of a reliability improvement. Section 3.3 explains the interaction of the effects of these changes on passengers, operators and governments and Section 3.4 demonstrates how this can be incorporated into a cost-benefit analysis.

3.1 Values of changes

It is clear from literature (Bates et al., 2001; Rietveld et al., 2001; Van Loon et al., 2011) that reliability is valued by public transit travelers and plays a role in their decision making. While it is generally agreed that reliability is valued, it is not often considered in cost-benefit analyses (Van Oort and Van Leusden, 2012). The main reason for this is the lack of an agreed upon value. This stems from the range of possible reliability indicators, different methods for collecting data and different theoretical approaches.

3.1.1 Reliability indicators

Bates et al. (2001) state that one challenge of monetizing reliability is which variable is used to represent reliability. They ask the question if it should be represented by one variable or a set of variables and how does it relate to the valuation of time?

Van Loon et al. (2011) show that the various ways of measuring reliability are correlated, but the correlations are often low. They use six indicators: Percent delayed more than 3 minutes, Percent very delayed (more than 9 minutes), Average delay of all trains, Average delay of delayed trains, Standard deviation and 80th-50th percentile. Very delayed and Average delay of all trains shows the largest correlation with delayed more than 3 minutes (used by the NS). 80th-50th percentile (a Reliability Buffer Time measure) has the strongest correlation...
with the change in the number of season-ticket holders. A 10% improvement in this indicator results in a 1.47% increase in the number of season ticket holders.

Standard deviation is used to indicate reliability by the Dutch Ministry of Infrastructure and the Environment (Kennisinstuut voor Mobiliteitsbeleid, 2013). While reliability buffer time might be more indicative of a passenger’s value of reliability, following the standard set by the Ministry ensures that multiples projects would be compared using the same statistic.

3.1.2 Type of studies

Bates et al. (2001) review the research surrounding traveler’s valuation of travel time reliability. They show that the measurement of the valuation of reliability is usually done through Stated Preference (SP) or Revealed Preference (RP) methods.

Generally Revealed Preference methods are preferred for more suitable data, however it is difficult to find real choice situations that allow statistically reliable estimates. Stated Preference methods allow for greater flexibility, and studies have generally shown they more or less corroborate with RP studies.

Early stated preference studies involved presenting hypothetical situations with different levels of reliability, and asking a hypothetical traveler to choose (Black and Towriss, 1991; Small et al., 1995; Small, 1999). The main drawback with these is that it that much depends on how the questions are asked and the respondents reaction to the presentation of the survey.

3.1.3 Approaches to the valuation of reliability

Li et al. (2010) identify three theoretical frameworks that have been used: the mean variance model, the scheduling model and the mean lateness model. They are briefly discussed here, and then it is explained that the mean variance model is the most relevant in the case of this research.

The mean variance model

Jackson and Jucker (1982) proposed a framework in which utility, $U$, is a function of mean travel time and the variation of travel time. The assumption here is that travelers make a trade-off between expected travel time and variability of travel time. This was extended by Senna (1994) and Small (1999) using the standard deviation for variance and a third term for general cost.

$$U = \beta_T E(T) + \beta_{SD} SD(T) + \beta_C C$$

(3.1)

where $\beta_T, \beta_{SD}$, and $\beta_C$ are parameters for the expected travel time $E(T)$, the standard deviation of travel time $SD(T)$ and the travel cost $C$.

Here it is possible that the standard deviation could be replaced by a different statistical representation of the width of the distribution. For example, Van Loon et al. (2011) found that the 80th-50th percentile showed the highest correlation (out of 6 possible indicators) with rail passenger behavior (change in number of season ticket holders).

Regardless of the statistic used for the distribution, the value of time will be $\beta_T \times \beta_C$ and the value of reliability will be $\beta_{SD} \times \beta_C$. This leads to a term called the reliability ratio, which is the ratio between the value of reliability and the value of time.
\[ R = \frac{\beta_{SD}}{\beta_T} \] (3.2)

Estimated reliability ratios have varied across studies. De Jong et al. (2009) suggested that agreed upon (by “experts”) values of reliability are 0.8 for car travel and 1.4 for public transit. Bates et al. (2001) suggested 1.3 for car travel and not higher than 2.0 for public transit.

The Dutch Ministry of Infrastructure and the Environment has recently published values of reliability along with their new values of time (Significance et al., 2013; Kennisinstuut voor Mobilitietsbelied, 2013). These were based on a stated preference research. The reliability ratio for train passengers and for urban public transport travelers (bus, tram and metro) are presented separately, and are both 0.6.

**The scheduling model**

The scheduling model takes into account the consequences of unreliable travel time. The scheduling model assumes that travelers experience disutility from arriving either before or after their preferred arrival time (Small, 1982). While the model by Small (1982) relates to traveler choice under certainty, an extension was made by Noland and Small (1995) to account for the distribution of travel time.

![Figure 3.1: The scheduling approach (Small, 1982)](image)

**Mean lateness model**

The mean lateness approach measures the value of reliability by the mean lateness at departure or arrival and is becoming the standard approach for trains in the UK (R. and N., 2009). The mean earliness (negative lateness) is not considered.

\[ U = \lambda T_{sched} + \mu L \] (3.3)
where $\lambda$ and $\mu$ are parameters to be estimated, $T^{\text{sched}}$ is the scheduled journey time and $\bar{L}$ is the mean lateness and the destination train station.

This model is similar to the “average delay of all trains” indicator as discussed in Van Loon et al. (2011).

**Synthesis**

The mean variance approach is the best fit with the passenger centered reliability indicators used in this thesis, additional travel time and reliability buffer time. In Equation 3.1 it should be noted that expected travel time is equal to scheduled travel time plus additional travel time.

$$E(T) = T^{\text{sched}} + T^{\text{add}}$$ (3.4)

Mean lateness is also a similar indicator to additional travel time, depending on how it is calculated. Mean lateness is the average delay, while additional travel time is the difference between the average actual travel time and scheduled travel time. Negative individual travel times contribute to additional travel time that would not contribute to mean lateness.

Use of the scheduling approach requires an idea of the preferred arrival time, and this theory does not fit with the assumptions and data used in this thesis.

### 3.2 Costs of changes

In general, the costs of improvements or changes to public transit systems are divided into infrastructure costs and operating costs. Infrastructure costs are incurred at the implementation of the project, as an investment, while operating costs are recurring.

Operating costs can be divided into three subcategories:

- Capacity costs (mostly number of vehicles needed to provide the service)
- Hourly costs (mostly cost of human resources)
- Kilometer costs (mostly cost of energy)

### 3.3 Effects of changes to reliability on passengers and operators

Van Nes (2002) uses game theory to analyze the operators and authorities perspective in the case of a multi-level network. In this article, two objectives (maximum profit and maximum social welfare) are used for a single operator or a multiple operator case. Van Nes (2002) found that benefits can be gained from cooperation, when the objective is profit, with a substantial profit increase to the higher level network. The highest profit for the higher level network is found when the lower level network has the goal of maximum social welfare. Because it benefits from a higher level of service at the urban level, the case is made for a cross subsidy from the higher level network to the lower level network.

Figure 3.2 shows an example of the consequences and benefits that are associated with each of the passenger groups (see Figure 4.2) and the two different operators. This example shows what may happen if the tram operator takes measures to increase the reliability for passengers making the tram to train connection.
3.3 Effects of changes to reliability on passengers and operators

**Action:** Increase reliability of transfer from Tram to Train

**Responsible:** Tram Operator

**Consequences:**

<table>
<thead>
<tr>
<th>Passenger Groups</th>
<th>Tram Operator</th>
<th>Train Operator</th>
<th>Government</th>
</tr>
</thead>
<tbody>
<tr>
<td>Costs and benefits from change in service</td>
<td>Costs of reliability improvements</td>
<td>No Cost</td>
<td>Change in social welfare (costs plus benefits)</td>
</tr>
<tr>
<td>Change in number of passengers = Change in revenues</td>
<td>Change in number of passengers = Change in revenues</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Effects related to specific passenger groups:**

<table>
<thead>
<tr>
<th>Passenger Groups</th>
<th>Tram</th>
<th>Train</th>
<th>Tram</th>
<th>Train</th>
<th>Tram</th>
<th>Train</th>
<th>Tram</th>
<th>Train</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tram Change in Service</td>
<td>Increase Reliability</td>
<td>Tram Change in Revenue</td>
<td>Increase Revenue</td>
<td>Tram -</td>
<td>Increase Revenue</td>
<td>Tram Social Welfare Change</td>
<td>Social Welfare Increase</td>
<td></td>
</tr>
<tr>
<td>Train Change in Reliability</td>
<td>-</td>
<td>Train Change in Revenue</td>
<td>-</td>
<td>Train Change in Revenue</td>
<td>-</td>
<td>Train Social Welfare Change</td>
<td>-</td>
<td></td>
</tr>
</tbody>
</table>

**Figure 3.2:** The main costs and benefits to each passenger group and to both the tram and train operators.

A change in reliability for one of the passenger groups may change the service (and the reliability) for the other passenger groups. This could have a positive or negative effect. For example, a holding point may make the connection more reliable for the connecting passengers, but will add some in-vehicle time to the through passengers.

In this example, it is assumed that the tram operator is responsible for the costs of the reliability increase. The tram operator also may experience a change in passenger volumes depending on a level of service increase or decrease for specific passenger groups. This change in passenger volume, leads to a change in revenue. All three groups of passengers that use the tram for all or part of their journey may change in size. In this case revenue from the tram-train transferring passengers will increase and revenue from the other two groups may decrease, if there is a loss in level of service.

In this scenario, the train operator is responsible for no costs, but may gain some revenue benefits from increased ridership. The number of passengers transferring to the train from the tram will increase but the number of passengers transferring from tram to train may decrease, depending on the nature of the changes in service. Because there is no change to the train service, revenue from the through train passengers will not change. Revenues from the through tram passengers are, of course, not relevant to the train operator.

In theory, the government is concerned with the overall costs and benefits of an improvement measure. While the passengers may only care about their changes in costs and benefits, and the operators may only care about changes in revenue, the government has to consider
everything, as they are responsible for the well-being of their citizens both by ensuring quality transit service for transit users and responsible use of taxpayer money. Depending on the nature of the relationship between the government and the transit operator, the government may have a different level of involvement in the ability to make choices regarding costs and level of service.

This example has been discussed in the context of unidirectional flows, as the examples in Figure 4.2. It should be noted that a passenger transferring from the tram to the train in the morning peak, will most likely be making the return journey in the evening peak and transferring from train to tram. Here, it is assumed that changes to the service will affect the evening peak “outbound” journey in the same way that they affect the morning peak “inbound” journey. In other words an improvement in service directed at a passenger group in the morning peak will be accompanied with an equal improvement in service for the opposite direction of the same route.

### 3.4 CBA Framework

Figure 3.3 shows an example format of the cost-benefit, or cost-effectiveness analysis. It is divided into sections regarding the operators and passengers, and further divided into sections for the multiple operators and multiple passenger groups in the system. In this way, the cost-effectiveness or cost-benefit ratio can be calculated for specific combinations of passengers and operators, or for the whole system.

The costs to operators (or benefits in the case of new revenues) for a set of changes in service are easy to compare and are in Euros.

The costs and benefits to passengers are made up of actual travel time components (scheduled travel time and additional travel time) as well as the variability in travel times, represented by reliability buffer time. This divides the travel time benefit into three parts, in line with the mean variance approach. This approach is also demonstrated in Van Oort and Van Leusden (2012) and is consistent with current Dutch policy which includes values for travel time and for reliability, measured as the standard deviation of travel time (Significance et al., 2013; Kennisinstuut voor Mobiliteitsbelied, 2013).

This analysis is set up so that each of these categories can have a weight. In general a change of a minute of reliability buffer time or standard deviation will be valued differently than a change of a minute of scheduled travel time. The weight used in this case will be the reliability ratio. By separating scheduled travel time and additional travel time, this framework allows for the value of additional travel time to be different. In the example case (Figure 3.3), the passenger indicators are calculated in minutes (and also “equivalent minutes”) when multiplied by the weight.

The time elements are monetized using the value of time. This leads to a cost-benefit analysis which can be indicated in two ways: benefits — costs and benefit to cost ratio $\text{CBR}$.

\[
\text{BCR} = \frac{\text{benefits}}{\text{costs}}
\]

### 3.5 Conclusions from Costs and Benefits

Reliability is not often included in cost-benefit analysis, even though it has been demonstrated to be of value to passengers. The main reason for this is the lack of consensus in research of

Aaron Lee

Master of Science Thesis
3.5 Conclusions from Costs and Benefits

<table>
<thead>
<tr>
<th>Example Cost Benefit Analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operators</td>
</tr>
<tr>
<td>New Revenue</td>
</tr>
<tr>
<td>Infrastructure</td>
</tr>
<tr>
<td>Operating</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Total Operators</td>
</tr>
<tr>
<td>Passengers</td>
</tr>
<tr>
<td>Weight</td>
</tr>
<tr>
<td>Scheduled Travel Time</td>
</tr>
<tr>
<td>Additional Travel Time</td>
</tr>
<tr>
<td>Reliability Buffer Time</td>
</tr>
<tr>
<td>Total Passengers</td>
</tr>
</tbody>
</table>

Figure 3.3: Example cost-benefit analysis with the impacts of reliability

A value for the distribution of travel times from a specific trip. In this research the reliability ratio is 0.6 (Significance et al., 2013; Kennisinstuut voor Mobilitietsbelied, 2013), with the understanding that not enough research has been done to put a complete faith in this value. An example cost-benefit analysis using the method presented in this chapter is presented in Chapter 8.
Chapter 4

Calculations and Variables of Reliability for Transferring Passengers

This chapter leads to the calculation of passenger reliability for transferring passengers and presents an overview of the five major variables that affect reliability at a transfer. Extending the Van Oort (2011) model to include transfers is one of the main objectives of this thesis. These calculations will be used in Chapters 6 and 7 to calculate reliability for transferring passengers, alongside Van Oort’s calculations for direct passengers.

The calculation method is derived by systematically going through the transfer process from a passenger’s perspective, beginning with the travel time components of a public transit journey and demonstrating the differences between direct passengers and transferring passengers. Additional travel time for direct passengers is calculated as in Van Oort (2011), but calculating this for transfer passengers requires a different method.

Additional travel time from a transfer is calculated in three different ways depending on the headway characteristics of both lines: short-short, long-short, and long-long (also including short-long). It is assumed that headways are integer multiples of each other.

System total average additional travel time is the sum of the additional waiting time for direct passengers, the additional transfer time for transferring passengers and any additional in-vehicle time (due to holding) for all passengers.

The intricacies of the five most important variables that impact reliability at a transfer are discussed at the end of the chapter in Section 4.5.

4.1 Travel Time Components

A passengers door-to-door public transit travel time can be broken down into several pieces: access time, waiting time, in-vehicle time, transfer time and egress time (Figure 4.1). Transfer time can be split into walking time and waiting time, where the walking time represents the time needed for a passenger to move to the departing platform of the second leg. The in-vehicle time can be separated into in-vehicle time for each leg of the trip.

Access and egress time will not be considered in this work, but it should be noted that variation also exists in these segments of the journey. This work is focused on improvements that will reduce the variability of the trip time elements that are influenced by public transit...
operators.

<table>
<thead>
<tr>
<th>Access</th>
<th>Waiting</th>
<th>In-Vehicle (1)</th>
<th>Transfer (Walking)</th>
<th>Transfer (Waiting)</th>
<th>In-Vehicle (2)</th>
<th>Egress</th>
</tr>
</thead>
</table>

**Figure 4.1:** The travel time components that are considered in the calculation of reliability metrics

### 4.2 Passenger Groups

There are six groups of passengers that travel through a transfer point that are of interest in the multi-level train-tram case. Direct passengers are those that travel through the transfer point on one mode without transferring. Transferring passengers can transfer from tram to train or from train to tram. Boarding passengers are those that initiate their journey at the transfer point. Figure 4.2 shows a transfer of one tram line and one train line. This diagram considers passenger traffic moving in one direction, up and to the right.

**Figure 4.2:** The six passenger groups and their routes through a transfer point

Through passengers on the tram will be impacted if the tram schedule is altered in order to create a more reliable transfer. These passengers could be positively or negatively affected depending on if the change results in an increase or decrease in level of service for the through route.
Passengers transferring from tram to train will be impacted by the reliability of the transfer. The main impact variables are the scheduled transfer time, train headway, arrival distribution of the tram at the transfer station and departure distribution of the train. A change in these variables can positively or negatively affect transferring passengers.

Passengers transferring from train to tram are also impacted by the reliability of the transfer. The main impact variables are the same as the transfer in the opposite direction although the roles of the different modes are reversed. In the cases in Figure 4.2, a tram acting as the feeding service for the tram-train passengers then becomes the connecting service for the train-tram passengers. Because of this, the scheduled transfer time cannot be varied independently for each group of transferring passengers, so a trade-off may exist. A reliable tram-train transfer may decrease the reliability of the train-tram transfer.

Through passengers on the train will be impacted if the train schedule is changed, but will not be impacted by changes to the tram level of service. Changes to the train level of service, or service pattern, could have a positive effect on the reliability of a transfer.

Tram or train passengers that begin their journey at the station may be impacted differently than through passengers, depending on the change in service. For example, a holding point at the transfer point will add time for through passengers, but will decrease departure time variability for boarding passengers.

4.2.1 Travel time variability for through passengers

Ideally, actual passenger travel times should be calculated from door to door over a specific route. Van Oort (2011) assumes that the total travel time variability is a function of waiting time variability and in-vehicle time variability. These two factors lead to a distribution, from which additional travel time and reliability buffer time can be calculated. In this work, the same basic assumption will be used. For direct passengers, total additional travel time is a function of additional waiting time and additional in-vehicle time.

4.2.2 Travel time variability for transferring passengers

Figure 4.3 shows several ways that variation in each of the travel time components can lead to variation of arrival time at the destination stop. The scheduled times are shown at the top.

The first scenarios show that the variation in travel times of waiting time and in-vehicle time over the first leg do not affect the arrival time at the destination stop, provided the connection is not missed. A positive additional in-vehicle time, leads to an equally less amount of transfer time, while a negative additional in-vehicle time leads to an equally more amount of transfer time.

The third and fourth scenarios show two ways that the individual components can have an affect on the final travel time variation. Additional transfer time, due to a late departure of the connecting vehicle, leads directly to additional travel time. Additional in-vehicle time, on the second leg, also leads directly to additional travel time.

A missed connection means that the passenger will have to wait for the next vehicle, leading to an increase in transfer time, and increase in travel time.

For transferring passengers, the final travel time distribution, which determines both additional travel time and reliability buffer time, is a function of whether or not the connection is made or missed, the delay of the departure of the connecting vehicle and the additional in-vehicle travel time of the second leg of the trip.

Master of Science Thesis
Aaron Lee
4.2.3 Passenger perspective

The chain of trip time elements can also be discussed in the context of the passenger’s perception. In this case, if an individual trip time segment is longer than expected, this can affect the perceived quality of the service, even if the extra time is negated in a subsequent trip segment. For example, in Figure 4.3, additional transfer time due to early arrival may not be perceived in the same way as additional in-vehicle time on the first leg, even though they both lead to the same arrival time at the destination stop.

For use in a mode choice, or route choice mode, it would be beneficial to add weights to the different travel time components. However, here the interest is in actual travel times, to be used to calculate passenger benefits. For this reason, weights are not given to individual travel time segments.

4.3 Calculation Framework

Additional Travel Time was calculated in Van Oort (2011) as the sum of Additional Waiting Time and Additional In-Vehicle Time. In this section, this framework is extended to include Additional Transfer Time for transferring passengers. The calculation framework is shown in Figure 4.4. Additional Travel Time for direct passengers is calculated in the same way as in Van Oort (2011), with different methods for short and long headways. Transfer passengers are calculated separately for each specific transfer group. Here there are three different calculations depending on headway characteristics of both lines. Additional In-Vehicle time is only calculated in the case of holding and is calculated for all passengers traveling through a holding point, including both direct and transfer passengers. The different calculations are derived in the following subsections.
Figure 4.4: The framework used for the calculation of additional travel time and reliability buffer time depending on the network characteristics and passenger types
4.3.1 Additional Waiting Time: for direct passengers

Passenger waiting time at a stop is the difference between the passenger’s arrival time at the stop and the departure time of the next vehicle (assuming the passenger is able to board that vehicle). Passengers arrive at stops according to a distribution and vehicles depart according to a distribution (Figure 4.5).

At the most basic level, the passenger arrival pattern can be random, where it is assumed that passengers arrive with no knowledge of the schedule, or schedule-based, where passengers arrive with the intention of taking a certain, scheduled, vehicle. A random passenger arrival pattern is often assumed in the case of short headways, while a schedule-based arrival pattern is used for long headways (longer than 12 minutes) (Vuchic, 2005).

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure4.5.png}
\caption{Additional waiting time at the initial stop}
\end{figure}

**Additional waiting time for short headways**

In the case of short headways and random arrivals, Van Oort (2011) uses the formula by Osuna and Newell (1972), which assumes a period of homogeneous scheduled departure times, a fixed passenger arrival and that all passengers are able to board the first arriving vehicle (Equation 4.1).

\[ E(T_{\text{waiting}}^{l,j}) = \frac{E(H_{\text{act}}^{l,j})}{2} \times \left(1 + CoV^2(H_{\text{act}}^{l,j})\right) \]  

(4.1)

where:

\[ E(T_{\text{waiting}}^{l,j}) = \text{Expected passenger waiting time at stop } j \text{ on line } l. \]
\[ CoV^2(H_{\text{act}}^{l,j}) = \text{Coefficient of variation (squared) of actual headways} \]
\[ E(H_{\text{act}}^{l,j}) = \text{Expected headway at stop } j \text{ on line } l. \]

As stated in Van Oort (2011), if the headways are perfectly regular, the coefficient of
variation will be zero and the average passenger waiting time will be equal to half of the headway (Equation 4.2).

\[ T_{l,j}^{\text{waiting}} = \frac{E\left(H_{l,j}^{\text{act}}\right)}{2} \]  

(4.2)

This represents the expected waiting time under perfectly reliable conditions. The additional waiting time due to unreliability is then the second term of Equation 4.1 and is shown in Equation 4.3

\[ E\left(T_{l,j}^{\text{add.waiting}}\right) = \frac{E\left(H_{l,j}^{\text{act}}\right)}{2} \times \left(C\text{ov}^2\left(H_{l,j}^{\text{act}}\right)\right) \]  

(4.3)

**Additional waiting time for long headways**

A different calculation is used to account for long headways and schedule-based passenger arrivals. In this case, passengers arrive at the stop according to a distribution around the scheduled departure time. These passengers can either make their planned vehicle, or miss it and wait for the next one.

In Van Oort (2011) the passenger arrival pattern is simplified to assume that all passengers arrive at a certain time \( \tau_{\text{early}} \) before the scheduled departure. It is also assumed that passengers do not experience additional travel time if the vehicle departs within the time frame between \( -\tau_{\text{early}} \) and \( \tau_{\text{late}} \). This represents the accepted departure interval of the vehicle, according to the passengers. A vehicle that departs before \( \tau_{\text{early}} \) causes all passengers to miss the vehicle and an additional travel time equal to the wait for the next vehicle. A vehicle that departs after \( \tau_{\text{late}} \) causes all passengers to have an additional travel time equal to the deviation of the actual departure time from the scheduled departure time.

The calculation for additional waiting time in the case of long headways, is shown in equation 4.4. This equation differs from Van Oort (2011) in that it uses the actual departure time of the next vehicle, instead of the scheduled headway.

\[ T_{l,i,j}^{\text{add.waiting}} = \begin{cases} 
D_{l,i+1,j}^{\text{act}} - D_{l,i,j}^{\text{sched}} & \text{if } d_{l,i,j}^{\text{departure}} \leq -\tau_{\text{early}} \\
0 & \text{if } -\tau_{\text{early}} < d_{l,i,j}^{\text{departure}} < \tau_{\text{late}} \\
D_{l,i,j}^{\text{act}} - D_{l,i,j}^{\text{sched}} & \text{if } d_{l,i,j}^{\text{departure}} \geq \tau_{\text{late}} 
\end{cases} \]  

(4.4)

**4.3.2 Additional In-Vehicle Travel Time**

Additional in-vehicle travel time is the difference between the expected and actual in vehicle travel times, as experienced by the passenger. Van Oort (2011) includes additional in-vehicle time only in the case of holding points, because additional in-vehicle time does not change unless this change is made to the schedule. In this case, all passengers traveling through a holding point will be given additional in-vehicle time.

\[ T_{l,i,j}^{\text{hold}} = \begin{cases} 
0 & \text{if } j \neq h_n \\
D_{l,i,j}^{\text{sched}} - D_{l,i,j}^{\text{act}} & \text{if } D_{l,i,j}^{\text{act}} \leq D_{l,i,j}^{\text{sched}} \\
0 & \text{if } D_{l,i,j}^{\text{act}} > D_{l,i,j}^{\text{sched}} \\
h_{\text{max}} & \text{if } D_{l,i,j}^{\text{act}} \leq D_{l,i,j}^{\text{sched}} - h_{\text{max}} 
\end{cases} \]  

(4.5)
\[
T_{l,j}^{\text{hold}} = \sum_i T_{i,l,i,j}^{\text{hold}} \times \alpha_{l,i,j}^{\text{through}}
\] (4.6)

\[
T_{l}^{\text{add,in-veh}} = \frac{\sum_j T_{l,j}^{\text{hold}} \times N_{l,j}^{\text{through}}}{N_{l}^{\text{board}}}
\] (4.7)

where:

\[T_{l,i,j}^{\text{hold}}\] = In vehicle time due to holding per passenger in vehicle \(i\) at stop \(j\) on line \(l\).

\(h_{\text{in}}\) = Stop number where holding is applied

\(h_{\text{max}}\) = Maximum allowed holding time

\[T_{l,j}^{\text{hold}}\] = Average in vehicle time per through passenger at stop \(j\)

\[\alpha_{l,i,j}^{\text{through}}\] = Proportion of through passengers in vehicle \(i\) at stop \(j\)

\[T_{l}^{\text{add,in-veh}}\] = Average additional in-vehicle time per passenger on line \(l\)

\[N_{l,j}^{\text{through}}\] = Total number of through passengers at stop \(j\)

\[N_{l}^{\text{board}}\] = Total number of passengers on line \(l\)

### 4.3.3 Additional transfer time: for transferring passengers

This section presents a closer view of a transfer from line \(l\) to line \(m\) at stop \(j\). It first describes some insights into the behavior of the situation, and then details the calculations of additional travel time for transferring passengers.

Figure 4.6 shows the stochastic elements that make up a transfer from one public transit line to another. The transfer consists of three stochastic timed events. The distribution of the arrival pattern of the first vehicle depends on the driving times of that vehicle prior to the station. Walking times between the vehicles will be stochastically distributed as not all passengers will be able to make the transfer at exactly the same speed. The distribution of the departing vehicle depends on its arrival time at the station, as well as boarding and alighting procedures and traffic.

For a passenger, the actual reliability at their final destination depends on the reliability of the transfer, and particularly the departure of the second leg of their trip. As long as a passenger makes their connection, the arrival time of their first vehicle does not affect their arrival time at their final destination. Any gain or loss in travel time from the first leg of their trip is negated by an opposite gain or loss in waiting time. The arrival time of the first vehicle does have an effect on whether or not a passenger misses the connection.

Figure 4.6 shows three possible passenger transfers. In the first case, when a passenger’s first vehicle arrives early, the passengers transfer time is extended by the amount of the early arrival, however this additional transfer time has no effect on the additional travel time at
the traveler's final destination. In the second case, the passenger's second vehicle departs late. This late departure is additional travel time that makes a part of the additional travel time at the final destination. In the third case, the passenger misses the connection. Here they have to wait until the actual departure time of the next vehicle, which is distributed around a scheduled departure time.

Additional travel time for transferring passengers is calculated in three ways, depending on the headway characteristics of both lines. In the case of a short-short headway configuration, it is assumed that passengers arrive at random at the first line, so the first vehicle cannot be made or missed. For the other cases: a short-long or long-long headway configuration and a long-short headway configuration, it is assumed that the passengers arrive at the first line according to the schedule so the first vehicle can be made or missed. This will affect the additional travel time for a transferring passenger and needs to be included in the calculations in this case.

**Additional transfer time: short-short headways**

The inputs to this calculation are as follows. Each vehicle \( i \) on line \( l \) has a scheduled arrival time, actual arrival time and a number of passengers that are transferring to line \( m \). Each vehicle \( i \) on line \( m \) has a scheduled departure time and an actual departure time.

\[
\begin{align*}
A_{\text{sched}, l,i,j} & = \text{Scheduled arrival time of vehicle } i \text{ at stop } j \text{ on line } l. \\
A_{\text{act}, l,i,j} & = \text{Actual arrival time of vehicle } i \text{ at stop } j \text{ on line } l. \\
N_{\text{trans}, l-m,i,j} & = \text{Number of passengers transferring from line } l \text{ to line } m \text{ in vehicle } i \text{ at stop } j. \\
D_{\text{sched}, m,i,j} & = \text{Scheduled departure time of vehicle } i \text{ at stop } j \text{ on line } m. \\
D_{\text{act}, m,i,j} & = \text{Actual departure time of vehicle } i \text{ at stop } j \text{ on line } m.
\end{align*}
\]
The additional travel time due to transferring is calculated differently for passengers that make their intended connection and passengers that miss their intended connection. The first part of the calculation divides passengers into these classes. The calculation model is built to account for a distribution in walking times, although a constant walking time is used throughout this work.

This is done by calculating the probability of making or missing the vehicle on line \( m \). In that case the number of passengers that make and miss the connection will be defined by Equations 4.8 and 4.9.

\[
P_{l-m,i,j}^{\text{make}} = N_{l-m,i,j}^{\text{trans}} \cdot P\left(t_{i,j}^{\text{platform}} \leq D_{m,i,j}^{\text{act}}\right) = \int_{-\infty}^{D_{m,i,j}^{\text{act}}} F(x) \, dx \quad (4.8)
\]

\[
P_{l-m,i,j}^{\text{miss}} = N_{l-m,i,j}^{\text{trans}} - P_{l-m,i,j}^{\text{make}} \quad (4.9)
\]

where:

- \( F(x) \) = Arrival distribution of passengers at the platform.
- \( P_{l-m,i,j}^{\text{make}} \) = Number of passengers that make their planned connection to line 2 from vehicle \( i \) at stop \( j \) on line \( l \).
- \( P_{l-m,i,j}^{\text{miss}} \) = Number of passengers that miss their planned connection to line 2 from vehicle \( i \) at stop \( j \) on line \( l \).
- \( N_{l-m,i,j}^{\text{trans}} \) = Number of passengers transferring from line \( l \) to line \( m \) from vehicle \( i \).

For simplicity, the initial calculations will assume no distribution of walking times. The arrival time at the departing platform will be the actual arrival time on line 1 plus the necessary walking time as in Muller and Furth (2009). This simplification is assumed because the amount of transfer walking time is not included in the improvement measures under the scope of this work.

Now that passengers are divided into groups, additional travel time can be calculated by equation 4.10.

\[
T_{\text{add,transfer}} = \begin{cases} 
D_{m,i,j}^{\text{act}} - D_{m,i,j}^{\text{sched}} & \text{for passengers that make train} \\
D_{m,i+1,j}^{\text{act}} - D_{m,i,j}^{\text{sched}} & \text{for passengers that miss train} 
\end{cases} \quad (4.10)
\]

**Short-long headways and Long-Long headways**

A short headway service transferring to a long headway service can be considered as the same as a long transferring to a long headway service from the passenger’s point of view (4.7). Because the second vehicle operates at a low frequency, the passenger is assumed to arrive at the stop according to the schedule. A passenger who misses their first vehicle will experience additional travel time equal to the second headway as shown in Figure 4.7. In the case (more likely in the long-long situation) that a passenger misses the first vehicle as well as the newly targeted second vehicle, their additional travel time will be twice the second headway. Specific
calculations for each case are found in Table 4.5. These calculations follow the standard set with the additional waiting and transfer calculations as the difference between the actual departure time of the departing vehicle and the scheduled departure of the expected vehicle.

**Figure 4.7:** Visual of additional transfer time for the case of transferring from a short to long (and long to long) headway

<table>
<thead>
<tr>
<th>Short-long and long-long</th>
<th>2nd Vehicle</th>
</tr>
</thead>
<tbody>
<tr>
<td>Make</td>
<td>Miss</td>
</tr>
<tr>
<td>1st Vehicle</td>
<td></td>
</tr>
<tr>
<td>Make</td>
<td>$D_{act}^{m,i,j} - D_{sched}^{m,i,j}$</td>
</tr>
<tr>
<td>Miss</td>
<td>$D_{act}^{m,i+1,j} - D_{sched}^{m,i,j}$</td>
</tr>
</tbody>
</table>

**Table 4.5:** Extension of the additional transfer time calculations for the case of transferring from a short to long headway or a long to long headway

**Long-short headways**

In this case, a passenger that misses their first connection will experience the additional travel time due to missing their connection and the additional travel time associated with the transfer. Because the second headway is short, the expected transfer time will be the same even if the first vehicle is missed. Here, the additional travel time is equal to the extra travel time from missing the first vehicle, plus the additional travel time at the transfer as calculated by Equation 4.10. Specific calculations for each case can be found in Table 4.6.

**4.3.4 Additional Travel Time for passenger groups and the network**

Here the reliability metric, average additional travel time per passenger is calculated for the different passenger groups and the entire network. Average additional travel time is calculated differently for through passengers and for transferring passengers.
Figure 4.8: Visual of additional transfer time for the case of transferring from a long to short headway

### Table 4.6: Extension of the additional transfer time calculations for the case of transferring from a long to short headway

<table>
<thead>
<tr>
<th></th>
<th>2nd Vehicle</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Make</td>
<td>Miss</td>
<td></td>
</tr>
<tr>
<td><strong>1st Vehicle</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Make</td>
<td>$D_{act}^{m,i,j} - D_{sched}^{m,i,j}$</td>
<td>$D_{act}^{m+1,i,j} - D_{sched}^{m+1,i,j}$</td>
<td></td>
</tr>
<tr>
<td>Miss</td>
<td>$H_{1}^{sched} + D_{act}^{m,i,j} - D_{sched}^{m,i,j}$</td>
<td>$H_{1}^{sched} + D_{act}^{m+1,i,j} - D_{sched}^{m+1,i,j}$</td>
<td></td>
</tr>
</tbody>
</table>

### ATT for through passengers

Additional waiting time for through passengers on each line is calculated first by stop and then by line. The additional waiting time per stop is calculated by 4.3 in the case of short headways and 4.4 in the case of long headways. The additional in-vehicle time applies only in the case that holding points are applied.

The average additional waiting time per passenger for through passengers on a line $l$ is the total additional travel time (Equation 4.12) on the line divided by the total number of through passenger boardings (Equation 4.13).

$$T_{add,waiting}^{l,i,j} = \sum_i T_{add,waiting}^{l,i,j} \times \alpha_{board}^{l,i,j}$$  \hspace{1cm} (4.11)

$$T_{add,total}^{l} = T_{add,in-veh}^{l} + \sum_j T_{add,waiting}^{l,j} \times N_{board}^{l,j}$$  \hspace{1cm} (4.12)

$$T_{add}^{l} = \frac{T_{add,through,total}^{l}}{N_{board}^{l}}$$  \hspace{1cm} (4.13)

where:

- $T_{add,total}^{l} = \text{Total additional travel time for direct passengers on line } l$
- $T_{add}^{l} = \text{Average additional travel time for direct passengers on line } l$
\( T_{\text{add,waiting}} \) = Average additional travel time for through passengers on line \( l \)

\( \alpha_{\text{board}}^{i,j} \) = Proportion of direct passenger boardings for vehicle \( i \) at stop \( j \)

\( N_{\text{board}}^{l,j} \) = Number of direct passenger boardings at stop \( j \)

\( N_{\text{board}}^{l} \) = Total number of direct passenger boardings

**ATT for transferring passengers**

Additional travel time for transferring passengers depends on the headway characteristics of both lines as shown in Tables 4.5 and 4.6. Equations 4.14 and 4.15 shows that additional travel time for transferring passengers from line \( l \) to line \( m \) is the sum of additional in-vehicle time on the second leg of their journey and the total additional transfer time.

\[
T_{\text{add,transfer,total}}^{l-m} = T_{\text{add,in-veh}}^{m} + \sum_{i} T_{\text{add,transfer}}^{l-m,i,j} \times N_{\text{trans}}^{l-m,i,j} \quad (4.14)
\]

\[
T_{\text{add,transfer}}^{l-m} = \frac{T_{\text{add,transfer,total}}^{l-m}}{N_{\text{trans}}^{l-m,j}} \quad (4.15)
\]

where:

\( T_{\text{add,total}}^{l-m} \) = Total additional travel time for passengers transferring from line \( l \) to line \( m \)

\( T_{\text{add}}^{l-m} \) = Average additional travel time for passengers transferring from line \( l \) to line \( m \)

\( T_{\text{add,transfer}}^{l-m,i,j} \) = Total additional transfer time for passengers transferring from line \( l \) to line \( m \) from vehicle \( i \)

\( N_{\text{trans}}^{l-m,i,j} \) = Number of passengers transferring from line \( l \) to line \( m \) from vehicle \( i \)

\( N_{\text{trans}}^{l-m,j} \) = Total number of passengers transferring from line \( l \) to line \( m \)

**ATT for network**

The average additional travel time per passenger for the entire network is the sum of all of the total additional travel times divided by the total number of individual passengers that use the network (Equation 4.16).

\[
T_{\text{add}} = \sum_{l,l-m} \frac{T_{l}^{\text{add,total}} + T_{l-m}^{\text{add,total}}}{N_{l}^{\text{board}} + N_{l-m,j}^{\text{trans}}} \quad (4.16)
\]
4.4 Reliability buffer time for transfer passengers

The definition of Reliability Buffer Time is the difference between the 95th percentile of travel time and the median travel time (Furth and Muller, 2006; Uniman et al., 2010). Reliability Buffer Time is calculated from the distribution of the additional travel times.

To calculate Reliability Buffer Time for a transfer, the distribution of individual additional transfer times is used as calculated in Section 4.3.3.

\[ RBT_{\text{transfer}} = T_{\text{add,transfer},95\text{th}} - T_{\text{add,transfer},50\text{th}} \] (4.17)

To calculate Reliability Buffer Time for direct passengers, the distribution of individual additional waiting times is used as calculated in Section 4.3.1.

\[ RBT_{\text{waiting}} = T_{\text{add,waiting},95\text{th}} - T_{\text{add,waiting},50\text{th}} \] (4.18)

To calculate Reliability Buffer Time for multiple passenger groups (All transfer passengers, all direct passengers, system total passengers), the individual additional travel times of each distribution are combined.

4.5 Variables leading to travel time variation

Based on the calculations and analysis of a transfer point, the major variables that can impact the reliability of a transfer need to be identified. The biggest reliability related consequence for passengers is whether or not they make or miss their connection.

There are 5 major variables that play an important role in the travel time distribution of transferring passengers. They are:

1. Scheduled transfer time
2. Scheduled headways on both lines
3. Variation of the distribution of vehicle arrival and departure times
4. Transfer walking time
5. Number of passengers at the given transfer

The first two stem from the stochastic operations and processes of a transit system. The next two are schedule related and the third is demand related, and impacts the magnitude of the importance of a certain transfer.

The five variables are summarized in Table 4.9 along with their causes and effects.

4.5.1 Scheduled transfer time

Varying the scheduled transfer time leads to a change in the amount of passengers that make or miss their intended connection, and will have an effect on the distribution of passenger travel times. A tighter scheduled transfer time results in a greater chance of passengers missing the connection, while a longer scheduled transfer time results in a greater chance of passengers making their intended connection.
4.5 Variables leading to travel time variation

<table>
<thead>
<tr>
<th>Cause</th>
<th>Variable</th>
<th>Effect</th>
</tr>
</thead>
<tbody>
<tr>
<td>Schedule and network design</td>
<td>Scheduled transfer time</td>
<td>Increased scheduled transfer time leads to increased travel time but a lower probability of missing the transfer</td>
</tr>
<tr>
<td>Schedule and network design</td>
<td>Headways at transfer</td>
<td>Larger headways increase the magnitude of the negative effect of a missed transfer</td>
</tr>
<tr>
<td>For Tram: Slack in schedule,</td>
<td>Variation (standard deviation) of vehicle</td>
<td>Less variation on one or both lines can increase reliability</td>
</tr>
<tr>
<td>distance from terminal to</td>
<td>arrival and departure times</td>
<td></td>
</tr>
<tr>
<td>transfer point, location of</td>
<td></td>
<td></td>
</tr>
<tr>
<td>holding point For Train:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Punctuality at transfer point</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Transfer point layout and</td>
<td>Transfer walking time</td>
<td>Effects on probability of making a transfer</td>
</tr>
<tr>
<td>behavior of passengers</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Demand patterns and quality of</td>
<td>Percent of transferring passengers</td>
<td>Increases importance of a reliable transfer</td>
</tr>
<tr>
<td>service</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 4.9: The causes and effects of the 5 important variables for reliability at a transfer

Scheduled transfer time is calculated as the difference between the scheduled departure time of the second vehicle and the scheduled arrival time of the first vehicle.

$$ T_{sched,trans}^{l-m} = D_{sched}^{m,i,j} - A_{sched}^{l,i,j} (4.19) $$

4.5.2 Headways

The scheduled headways of both vehicles also play an impact in the final travel time distribution. The headway of the second vehicle is particularly important because it represents the consequence of missing the connection. In situations where passengers are assumed to arrive at the first line according to the schedule, the consequence of missing the first line is related to the headway of the first line.

Master of Science Thesis  
Aaron Lee
4.5.3 Variation of vehicle arrival and departure times

The distributions of arrival and departures times of vehicles play an important role in the distribution of passenger travel times. Even without the possibility of a passenger missing their preferred vehicle, a greater variation in vehicle departure times leads to a greater variation in passenger travel times.

In the case of the transfer, the variation of vehicle arrival and departure times on both lines has an impact.

At the transfer point, the distribution of arrival times of the first vehicle has an impact on whether or not a passenger makes their connection (see Figure 4.11). A wider distribution leads to more chances that the connection will be missed and the passenger will experience an additional headway of additional travel time.

Also at the transfer point, the distribution of departure times of the second vehicle has an impact on weather or not a passenger makes their connection. A wider distribution leads to more chance that the departing vehicle will depart before the passenger arrives at the platform, increasing the number of passengers that miss the connection (see Figure 4.12). Regardless of if a passenger makes or misses their connection, the distribution of the departure of the second vehicle also has an impact on the distribution of passenger travel times.

The distribution of the departure times of the first vehicle also has an impact on passenger...
4.5 Variables leading to travel time variation

Arrival pattern of vehicle  
Departure pattern of vehicle  
Passenger arrival at departing platform  
Waiting  
Walking  
Walking  
Waiting  
Walking  
Waiting  

Early arrival:  
Late departure of second vehicle:  
Missed connection:  

Varying the distribution of the departure of the second vehicle can lead to a change in the probability of making or missing the connection.

Figure 4.12: The standard deviation of arrival times of the first vehicle has an effect on whether or not a passenger makes their connection.

Varying the distribution of transfer walking time can lead to a change in the probability of making or missing the connection.

Figure 4.13: The amount or distribution of walking time has an effect on whether or not a passenger makes or misses their connection.

travel times in the case of long headways, or a combination of long and short headways, when passengers are assumed to arrive at their first vehicle according to the schedule. Here a wider distribution leads to more passengers missing their first vehicle, increasing the overall average travel time.

4.5.4 Transfer walking time

The transfer walking time distribution also has an effect on whether or not passengers make or miss their connection. Again a wider distribution leads to more passengers missing the connection and a wider overall distribution of travel times (Figure 4.13).

The length of transfer walking time is also important. A shorter transfer walking time means that the scheduled transfer time (from scheduled arrival of the first vehicle to scheduled departure of the second vehicle) can be shortened by the same amount with no change in reliability.

A transit authority or operator can change the walking time distribution by modifying the station layout. This requires a modification to the infrastructure. Although this change can result in a change in reliability, it is outside the scope for this research.
4.5.5 Proportion of Transferring passengers

Finally, the proportion of transferring passengers on each specific transfer plays a role in the overall impact. A transfer with a higher proportion of passengers will contribute more to the total additional travel time of the system.

4.6 Conclusions from Calculations and Variables

There are two main outputs from this chapter. First is the calculations that are used for additional travel time and reliability buffer time, in Chapters 6, 7 and 8. Second is the identification of the important variables of reliability at a transfer that are used as a framework for analyzing the results in Chapters 6 and 8.

From vehicle data and passenger data, reliability can be calculated for various passenger groups. For the purposes of this model, the way in which reliability is calculated depends on if a passenger does or does not transfer. After splitting those passengers, the calculation then depends on the headway characteristics of the line or lines involved.

The five major factors in determining reliability at a transfer are:

1. Variation of the distribution of vehicle arrival and departure times
2. Scheduled transfer time
3. Scheduled headways on both lines
4. Transfer walking time
5. Number of passengers at the given transfer

Chapter 6 demonstrates the way that these five variables interact with each other.
Chapter 5

Network and Input Data

This chapter details the network and the processing of the input data for both the hypothetical network and the real test case at the Den Haag HS station. The hypothetical network is used in scheduled transfer time and holding calculations in Chapters 6 and 7 and provides an environment where all variables can be controlled. The hypothetical network is designed to be similar to the test case at Den Haag HS which includes the crossing of tram line 9 of the (HTM) and the national train service (NS) towards Rotterdam and Leiden. Automatic Vehicle Locater (AVL) data from the HTM is used with a network surrounding the Den Haag HS station for the example in Chapter 8.

The necessary input data for the calculation model is:

1. Scheduled arrival times
2. Scheduled departure times
3. Actual vehicle arrival times
4. Actual vehicle departure times
5. Direct passenger boardings per stop
6. Direct passenger alightings per stop
7. Transfer passenger boardings per stop per specific transfer
8. Transfer passenger alightings per stop per specific transfer

This data must be generated for the hypothetical network. Section 5.1 details the generation of the network, the passenger data and the vehicle data that is used for hypothetical network calculations.

In the Den Haag HS case, vehicle and passenger data is given for the tram line in both directions, but not for the train line. Section 5.2 details how the vehicle data for the train is generated and the assumption that is made for the number of transferring passengers.
5.1 The Hypothetical Network

The network consists of a two line network, with traffic going in both directions along each line. The line passing from left to right, in Figure 5.1 is an urban transit line (tram), while the line passing from bottom to top is a regional train line. For reference, the lines are numbered in Table 5.1.

For the initial case, the tram line includes 30 evenly spaced stops and a 60 minute total running time, as in Van Oort et al. (2012). The train line includes 5 evenly spaced stops with a 50 minute total running time. The transfer point is set at stop 18 on tram line 1, stop 13 on tram line 2 and stop 3 on train lines 3 and 4. The transfer points on the tram line are set to be on the edge of the city center, a common location for the train station in Dutch cities.

![Figure 5.1: The hypothetical network used for initial calculations. The dashed line represents the tram line and the solid line represents the train line](image)

<table>
<thead>
<tr>
<th>Line</th>
<th>Type</th>
<th>Direction</th>
<th>Transfer Stop</th>
</tr>
</thead>
<tbody>
<tr>
<td>Line 1</td>
<td>Tram</td>
<td>Left to Right</td>
<td>18</td>
</tr>
<tr>
<td>Line 2</td>
<td>Tram</td>
<td>Right to Left</td>
<td>13</td>
</tr>
<tr>
<td>Line 3</td>
<td>Train</td>
<td>Bottom to Top</td>
<td>3</td>
</tr>
<tr>
<td>Line 4</td>
<td>Train</td>
<td>Bottom to Top</td>
<td>3</td>
</tr>
</tbody>
</table>

Table 5.1: Numbering of lines and their relation to the network diagram

5.1.1 Passenger Flows

The base passenger flows on the tram line follow a typical radial line (Van Oort et al., 2012) where most boardings occur in the first part of the line, and alightings occur in the second part of the line. The base passenger flows on the train line are set for equal boardings and alightings at each stop. Transfer flows are added on top of this base pattern.

The following steps demonstrate the derivation of the passenger flows for the different passenger groups on the tram line.
5.1 The Hypothetical Network

Figure 5.2: Boardings of different passenger groups for the hypothetical tram line.

1. 2/3 of direct passengers board between stops 1-15
2. 2/3 of direct passengers alight between stops 16-30
3. The transfer point is at stop 18 for line 1, and stop 13 for line 2 (in the opposite direction)
4. The number of transferring passengers (Fig. 5.2) is 20% of the through passenger boardings at each stop until the transfer point.
5. The total number of transferring passengers (alighting from the tram at the transfer point) is the sum of all transferring passengers.
6. The number of alighting “transferred” passengers is 20% of the alightings at each stop following the transfer point.
7. The number of transferred passengers (boarding at the transfer point in Fig. 5.2) is equal to the total number of downstream alighting transfer passengers.
8. Each tram line feeds passengers to two transfers and receives passengers from two transfers. The total number of transfers are split evenly between the two transfers.

The following steps demonstrate the derivation of the passenger flows for the different passenger groups on the train line.

1. Through passenger boardings and alightings are the same for each stop.
2. The transfer point is at stop 3
3. The number of transferring passengers and transferred passengers is equal to the total on the tram line

4. The boardings and alightings of transferring and transferred passengers are split evenly among the preceding or remaining stops

This process leads to transfer passengers accounting for a total of 32.2% of tram passengers in the system. The percent of direct passengers on the train is neglected from this calculation because the reliability for direct train passengers is never changed throughout this thesis and the number of direct passengers on the train is an arbitrary number. Table 5.2 lists the percentage of passengers in each passenger group.

<table>
<thead>
<tr>
<th>Passenger Group</th>
<th>Percent of Total Tram Passengers</th>
<th>Boarding Line</th>
<th>Alighting Line</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transfer A</td>
<td>5.3 %</td>
<td>Line 3</td>
<td>Line 2</td>
</tr>
<tr>
<td>Transfer C</td>
<td>5.3 %</td>
<td>Line 4</td>
<td>Line 2</td>
</tr>
<tr>
<td>Transfer D</td>
<td>2.9 %</td>
<td>Line 2</td>
<td>Line 4</td>
</tr>
<tr>
<td>Transfer F</td>
<td>2.9 %</td>
<td>Line 2</td>
<td>Line 3</td>
</tr>
<tr>
<td>Transfer G</td>
<td>2.9 %</td>
<td>Line 3</td>
<td>Line 1</td>
</tr>
<tr>
<td>Transfer I</td>
<td>2.9 %</td>
<td>Line 4</td>
<td>Line 1</td>
</tr>
<tr>
<td>Transfer J</td>
<td>5.0 %</td>
<td>Line 1</td>
<td>Line 4</td>
</tr>
<tr>
<td>Transfer L</td>
<td>5.0 %</td>
<td>Line 1</td>
<td>Line 3</td>
</tr>
<tr>
<td>Direct 1</td>
<td>33.9 %</td>
<td>Line 1</td>
<td>Line 1</td>
</tr>
<tr>
<td>Direct 2</td>
<td>33.9 %</td>
<td>Line 2</td>
<td>Line 2</td>
</tr>
<tr>
<td>Direct 3</td>
<td>n/a</td>
<td>Line 3</td>
<td>Line 3</td>
</tr>
<tr>
<td>Direct 4</td>
<td>n/a</td>
<td>Line 4</td>
<td>Line 4</td>
</tr>
<tr>
<td>All Transfers</td>
<td>32.2 %</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Direct Tram</td>
<td>67.8 %</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total Tram</td>
<td>100.00 %</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 5.2: Percent of tram passengers in each passenger group for the hypothetical network. Pictures of the passenger groups are found in Figure 5.3

### 5.1.2 Scheduled and Actual arrival and departure times

Scheduled running times are determined from the desired headway and the distance between stops, which has already been set for these two lines. Headways can be varied for each line, depending on the desired circumstances. In addition, the number of unique vehicle trips can be varied to create a fictitious time period for study. For example, an hour period can be studied by creating 6 vehicle trips with a headway of 10 minutes. Departure times are calculated as follows:

\[
D_{l,i,j}^{\text{sched}} = D_{l,i,j-1}^{\text{sched}} + R_l^{\text{sched}} \tag{5.1}
\]

and

\[
D_{l,i+1,j}^{\text{sched}} = D_{l,i,j}^{\text{sched}} + H_l^{\text{sched}} \tag{5.2}
\]

where:
5.1 The Hypothetical Network

Figure 5.3: A graphic indicating the direction of each transfer. For the rest of this thesis, passenger groups will be represented by symbols, so that it is clear when a certain passenger group is included in an analysis.
\[ R_{l}^{sched} = \text{Running time between stops on line } l \]
\[ H_{l}^{sched} = \text{Scheduled headway on line } l. \]

The actual trip times are assumed to be Gaussian distributed as in Abkowitz et al. (1987) and Strathman et al. (2002). These are calculated for each link on each trip so that:

\[ D_{l,i,1}^{act} = D_{l,i,1}^{sched} + R_{l}^{sched} \times r_{\mu,\sigma} \]  
(5.3)

at the first stop. And:

\[ D_{l,i,j}^{act} = D_{l,i,j-1}^{act} + R_{l}^{sched} \times r_{\mu,\sigma} \]  
(5.4)

at each additional stop. The value \( r_{\mu,\sigma} \) is a random number with mean \( \mu = 0 \) and standard deviation \( \sigma \). The standard deviation can be varied depending on the desired situation.

The train schedules are then adjusted so that they are synchronized with the tram schedules. This is done so that the arrival of the first train at the transfer stop is between the arrival of the first and second trams at the transfer stop.

5.1.3 Parameters for hypothetical network

The main parameters used for the hypothetical network are noted in Table 5.4.

“Tearly” and “Tlate” are the values needed for calculation of reliability in the long headway scenarios. “Headway” represents the scheduled headway of the line. “Stop Distance (min)” represents the scheduled time between each stop. “Standard Deviation” represents the standard deviation used to calculate actual vehicle travel times as a percent of running time. “Number of stops” is the number of stops on the line. “Number of trips” is the number of unique vehicles that travel through the line. “Transfer Walking Time” represents the transfer walking time input to the reliability calculations and “Walking Standard Deviation” represents the randomization of this walking time. “Transfer stop” denotes the stop number of the transfer point from the beginning of the line. “Dwell time” represents the difference between the scheduled arrival and departure and “Minimum Dwell Time” represents the minimum difference between the actual arrival and departure times.

5.2 Input data for the real network

This section details the process of formatting the data and setting the network for the example case. This section discusses first the scheduled and actual departure departure times of the vehicles, and then the passenger boardings and alightings.

Automatic vehicle location (AVL) data was provided from the HTM, the transit authority in The Hague, Netherlands. The data provided included actual and scheduled arrival and departure times for both directions of the Tram line 9 for an 8 day period in November 2012. Data also included average passenger boardings and alightings for the month, for each one-hour block.

5.2.1 Vehicle Departure and Arrival Times

Scheduled and actual tram data was input directly. Actual train arrival and departure times were not available, so the train schedule, arrivals and departures were simulated.

Aaron Lee  
Master of Science Thesis
A hypothetical train schedule was created with the intention to mimic the on-time performance of the Dutch railways (NS). A log-normal distribution for train arrival times was used, as suggested by Yuan et al. (2006). The choice for standard deviation (as a percent of running time) of these random numbers was made so that the distribution would represent the on-time percentage of the NS as faithfully as possible. NS on-time figures are something around 93% of trains depart within three minutes of the scheduled departure time.

Scheduled departure times are calculated from Equations 5.1-5.2, and using the same 5-stop line as was used in Chapter 6. This line closely represents the intercity line immediately surrounding Den Haag HS, where stations are more or less 10 minutes apart.

At the first stop the actual arrival and departure of the vehicle are calculated from the schedule. At the first stop, the actual arrival time is:

\[ A_{i,1}^{act} = D_{i,1}^{act} - T_{dwell}^{l} + r_{\mu,\sigma}^{\logn} \]  

(5.5)

And the actual departure time is:

\[ D_{i,1}^{act} = \begin{cases} 
A_{i,1}^{act} + T_{mindwell}^{l} & \text{if } A_{i,1}^{act} + T_{mindwell}^{l} > D_{i,1}^{act} \\
D_{i,1}^{act} & \text{if } A_{i,1}^{act} + T_{mindwell}^{l} < D_{i,1}^{act}
\end{cases} \]  

(5.6)

At each subsequent stop the actual arrival time is:

\[ A_{i,j}^{act} = D_{i,j-1}^{act} + R_{l}^{sched} - T_{dwell}^{l,j} + r_{\mu,\sigma}^{\logn} \]  

(5.7)

and the actual departure time is:

\[ D_{i,j}^{act} = \begin{cases} 
A_{i,j}^{act} + T_{mindwell}^{l} & \text{if } A_{i,j}^{act} + T_{mindwell}^{l} > D_{i,j}^{act} \\
D_{i,j}^{act} & \text{if } A_{i,j}^{act} + T_{mindwell}^{l} < D_{i,j}^{act}
\end{cases} \]  

(5.8)

where:

\[ R_{l}^{sched} = \text{Running time between scheduled departures on line } l \]
52 Network and Input Data

\[ H_{l}^{sched} = \text{Scheduled headway on line } l. \]

\[ T_{l,j}^{dwell} = \text{Scheduled dwell time at stop } j. \]

\[ T_{mindwell} = \text{Minimum dwell time for late running vehicles.} \]

\[ r_{\mu,\sigma}^{logn} = \text{A random number from a lognormal distribution} \]

with mean \( \mu \) and standard deviation \( \sigma \).

The parameters used for this network setup can be found in Table 5.6. The tram lines (1 and 2) were taken from the real data, while the train lines were created using the above procedure.

Train lines were shifted so that the scheduled departure times were equal to the scheduled departure times of the Intercity service between Amsterdam and Dordrecht at Den Haag HS. (An aside that sprinter trains arrive and depart at the same time.) 2 minutes was used for \( T_{l,j}^{dwell} \), at all stops, because this is the scheduled dwell time at Den Haag HS. 1 minute was assumed for \( T_{mindwell} \). The standard deviation for the lognormal running time distribution was chosen in order to give a close representation of the on time performance of the NS where 93% of trains depart within three minutes of the scheduled departure.

<table>
<thead>
<tr>
<th></th>
<th>Line 1</th>
<th>Line 2</th>
<th>Line 3</th>
<th>Line 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tearly</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>TLate</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Headway</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Stop Distance (min)</td>
<td>2</td>
<td>2</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Standard Deviation</td>
<td>-</td>
<td>-</td>
<td>.5</td>
<td>.5</td>
</tr>
<tr>
<td>Number of Stops</td>
<td>31</td>
<td>31</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Number of Trips</td>
<td>56</td>
<td>56</td>
<td>56</td>
<td>56</td>
</tr>
<tr>
<td>Transfer Walking Time</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Walking Standard Deviation</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Transfer Stop</td>
<td>17</td>
<td>14</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Dwell Time</td>
<td>0</td>
<td>0</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Min Dwell Time</td>
<td>-</td>
<td>-</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

Table 5.6: Parameters for varying the standard deviation on the tram line 2

5.2.2 Passenger Assignment

An OD-matrix was given for boardings and alightings at each stop in both directions of the tram lines. No information was given about transferring passengers. Because the calculation model works under the pretense that the number of passengers going through each specific transfer is known, an assumptions had to be made from the data to split transferring and direct passengers and to split transferring passengers into specific transfer groups.

This is done in the following way:

- Transfer boarding passengers at each stop is set at 100% of boarding passengers that alight at the transfer point.
5.3 Networks and Data: Conclusions

- Transfer alighting passengers at each stop is set at 100% of alighting passengers that board at the transfer point

- At the transfer point, these passengers are split 50-50 into the two possible transfers

In reality the number of passengers boarding or alighting at the transfer point (Den Haag HS) is probably not made up of 100% passengers that are transferring to or from the rail network. However, choosing 100% gives an opportunity to represent the maximum amount of possible transfer passengers.

Likewise the 50% split between the two transfer possibilities is not likely realistic. However, having a certain amount of transfer passengers at each route allows the average additional travel time to be calculated for passengers on that transfer. When used by a transit planner these numbers could be changed to more accurately reflect the best guess for specific transfer directions. In the next section, the effects of changing this split to 80% and 20% is demonstrated.

5.3 Networks and Data: Conclusions

This chapter has detailed the networks and data to be used with the calculation model as described in Chapter 4, and contains some of the assumptions that were made in the generation of this data. The generated passengers flows, timetables and vehicle times for the hypothetical network are used in calculations in Chapters 6 and 7. The passenger flows are assumed to be a typical radial line, with a percentage of passengers that transfer. Actual vehicle running times are determined from a normal distribution with a standard deviation of 20% of running time. The transfer stop is assumed to be just outside the center of the tram line.

The generated transfer passengers and train vehicle running times are combined with AVL data from the HTM for the example case in Chapter 8. The running times of the train are set from a log-normal distribution with a standard deviation that mimics the on time performance of the Dutch national railways (NS). It is assumed that all passengers boarding or alighting the tram at the transfer station are transferring to or from the railway. These passengers are evenly split among both rail directions.
Chapter 6

The Five Major Variables tested in a Hypothetical Network

This chapter explores the effects of synchronization of transfers on reliability by calculating reliability for varying scheduled transfer times. The five major variables, described in Chapter 4, are analyzed in this context. These variables are: scheduled transfer time, headways, variation of vehicle arrival and departures, amount of passengers and transfer walking time.

The aim of this chapter is to give a transit operator or authority some insights into how to choose a reliable transfer time in the schedule building process. The effects of the five major variables are discussed because no one situation will govern how an operator should act. Recommended actions will depend on the magnitude of the variables in a given situation.

The analysis uses the hypothetical network crossing of a train and a tram and simulation generated data, as shown in Chapter 5. For this case, the method of calculating additional travel time and reliability buffer time can be used to determine the scheduled transfer time that is most reliable for each individual transfer, and for the combination of transfers at the transfer point.

Scheduled transfer time is analyzed for both short (10 minutes) and long (15 minutes) headway conditions in Section 6.1. By shifting the tram schedules in both directions simultaneously, the four tram-to-train transfers are varied together, causing the four train-to-tram transfers to be varied in the opposite direction. The effects of the headway are discussed in Section 6.2. The variation of actual arrival and departure times for both lines involved in any given transfer has an effect that differs depending on the characteristics of the line, and that line's role in the transfer (first trip leg or second trip leg). This is discussed in Section 6.3. The effects of number of transferring passengers (Section 6.4) and walking time (Section 6.5) are fairly straightforward, but must be considered.

In Section 6.6 scheduled transfer time is plotted along with additional travel time and reliability buffer time. This clearly illustrates the trade-off between scheduled travel time and reliability.
6.1 Scheduled Transfer Time

Analyzing the effect of scheduled transfer time is one of the main goals of this thesis. At the simplest level, the scheduled transfer time can be varied for a single transfer. However, because the lines cross, changing the scheduled transfer time for one transfer has a direct effect on another transfer. In this section, results are presented for both short and long headways. In each case, results are presented for individual transfers, in order to show how the passengers on that specific transfer are affected by the scheduled transfer time, and for a combination of all transfer passengers, to show the trade-off between “opposite” transfers.

In all cases, average additional travel time is the primary indicator, and the 95th percentile of travel times, as the reliability buffer time, gives an indication of the width of the distribution of travel times.

In each of these cases, the train schedule was kept as a constant, while the tram schedules were shifted so that the scheduled transfer time varied between 0 minutes and the maximum of 1 minute less than a full headway. The shift was done so that groups of four transfers were varied together. As the four tram-to-train transfers (transfers A, C, G and I) increase, the four train-to-tram transfers (transfers D, J, F and L) decrease. Shifting a tram schedule in time to increase the transfer time from that tram to the train decreases the transfer time from the train to that tram.

6.1.1 Scheduled transfer time for short headways

Results for varying the scheduled transfer time in the short headway case are shown for two individual transfers in Figures 6.1 and 6.2. As expected, the results show that a transfer becomes more unreliable as the scheduled transfer time is decreased. Increasing the scheduled transfer time lowers the additional travel time and reliability buffer time, increasing reliability.

A difference can be seen in the shape of the curves in these two examples. Transfer D descends more steeply than Transfer A, but does not get as close to zero. The difference between the two is that Transfer D involves transferring to the train, where vehicles are not allowed to depart before the schedule. This means that fewer passengers miss their connections in tight transfers, because the connecting vehicle cannot depart early. For long transfer times, the average additional travel time does not approach zero, again because early departures are not allowed.

In Appendix A, Figures A.1 and A.2 show the graphs for other like transfers as superimposed onto the initial example graphs. This demonstrates that transfers to the train or transfers to the tram tend to follow the same pattern.

Because varying one transfer has an opposite effect on another transfer, it is interesting to look at the effects of all transfers together. Figure 6.3 shows the average additional travel time for all transfer passengers, while varying the scheduled transfer time of all transfers. Groups of 4 transfers are varied together. All of the train-to-tram transfers times are indicated by the top row of numbers on the horizontal axis, while the tram-to-tram transfers are indicated by the bottom row. The optimal point, in this case, is a 7 minute scheduled transfer time for train-tram transfers and a 4 minute transfer time for tram-train passengers.

The optimal point is located towards the side of the graph where tram-train transfer passengers have a tighter connection. The primary reason for the skew in this direction is that the train does not depart early, meaning that tighter connections for transfer towards the train are more reliable.
Figure 6.1: Additional travel time and reliability buffer time for passengers traveling through Transfer A, a train-to-tram transfer

Figure 6.2: Additional travel time and reliability buffer time for passengers traveling through Transfer D, a tram-to-train transfer
6.1.2 Scheduled transfer time for long headways

There are two main differences between scheduled transfer time for short headways and long headways. The first is the calculation method of additional travel time and reliability buffer time. For long headways, passengers are assumed to arrive according to the schedule so it is possible that they can make or miss both their initial vehicle and their transfer. The second is that the consequence for missing a connection is greater.

Figures 6.4 and 6.5 show the same two transfers as were seen in the short headway case. The same phenomenon is observed where the transfer to the train (Transfer D) is more reliable for a tighter transfer.

Two things can be noted about the reliability buffer time in this case. In the train to tram transfer, the 95th percentile of travel times drops steeply from hovering around 15 minutes, to around 3 minutes. Here it would appear that there is a big gain in reliability in moving the scheduled transfer time from 8 minutes to 9 minutes. This is misleading because of the nature of reliability buffer time. The distribution of passenger transfer times is actually made up of two groups, one of which is clustered around 0, for passengers that make their connection and another which is clustered around the headway of the connecting service, for passengers that miss their transfer. The 95th percentile of this distribution stays around 15 when the percentile is in this upper sub-distribution, but appears to drop quickly because there are not so many passengers with in between transfer times.

The tram to train transfer has some reliability buffer times that are well above the 15-minute range. These result from additional travel times for passengers who miss both their first vehicle and their connection. This part of the distribution was not seen in Transfer A because of the nature of the calculation model. Transfer A passengers originate on the train line. Since the train does not depart early, and passengers are assumed to make their vehicle if it departs any time after $\tau_{\text{early}}$, it is impossible for passengers to miss their connection when originating on the train line. This is a shortcoming of this assumption.

Figure 6.6 shows the average additional travel time and reliability buffer time for all transferring passengers in the long headway case. Similar to the case of short headways and for the same reason, the optimal point is towards the side of a shorter transfer for passengers transferring to the train. The same graph is not shown for the whole network because the effect of direct passengers is constant in this case and will not change the optimal point.

6.2 Headways

The headway of the second vehicle in a transfer has an important effect on the impact of missing the intended connection. Passengers that miss a connection to a long headway vehicle will suffer more than passengers who miss a connection to a short headway vehicle.

This effect is demonstrated by running three separate hypothetically generated timetables, with second vehicle headways of 10 minutes, 15 minutes and 20 minutes.

For this case, specific transfers were considered so as to identify the effect of the second headway on the passengers that are transferring to that headway. The transfers from each train direction to one tram direction (line 2) are used to demonstrate this.

As expected, an increase in the headway of the second vehicle relates to an increase in additional travel time for transferring passengers. Dividing the average additional time by the headway for each transfer shows that there is a direct relationship between headway and amount of average additional travel time, as demonstrated in Figure 6.7. This suggests that
6.2 Headways

Figure 6.3: Comparison of additional travel time and reliability buffer time all transfer passengers

Figure 6.4: Additional travel time and reliability buffer time for passengers traveling through Transfer A, a train-to-tram transfer

Master of Science Thesis
Aaron Lee
The Five Major Variables tested in a Hypothetical Network

Figure 6.5: Additional travel time and reliability buffer time for passengers traveling through Transfer D, a tram-to-train transfer

Figure 6.6: Comparison of additional travel time and reliability buffer time all transfer passengers
The effect of different second vehicle headways

The relation between additional travel time and headway

**Figure 6.7:** Average additional travel time for transfer specific passengers for three different headways (top) and the relation of average additional travel time to headway of the second vehicle (bottom)
the impact of an unreliable service have a greater impact on passengers when headways are larger.

Because of the assumptions made for the calculations, the headway of the first vehicle does not play a visible role. For short headways, the passenger is assumed to arrive at random at the first stop. In this case, only the headway of the second vehicle factors in the calculation. For the short-long headway combination, passengers are assumed to arrive at their first stop according to the vehicle that will make the shortest connection with the second line. Again, the headway of the first line does not directly factor in the calculation.

6.3 Variation of Vehicle Arrivals and Departures

The variation in vehicle arrivals and departures has an effect on the reliability of a transfer. To demonstrate this, a sensitivity analysis is carried out on the standard deviation of vehicle arrivals and departures.

Using 10 minute headways on both lines, Additional Travel Time and Reliability Buffer Time were calculated for standard deviation of actual vehicle times at 5% and 40% of running times. This was done separately for one tram line and one train line, because of the difference in control characteristics: the train line does not depart early. From this four cases are identified: varying the standard deviation of the train line as the first part or the second part of a transfer and varying the standard deviation of the tram line as the first part of the second part of a transfer.

Figure 6.8 shows a comparison of the results of the four different cases. Two different effects can be seen, depending on if the standard deviation is varied on the first or second line of the transfer. In the upper left and lower right, the standard deviation is varied along the first line of the transfer. In the other two graphs the standard deviation is varied along the second line of the transfer.

6.3.1 Standard deviation of the first line

Varying the standard deviation of the first line in a transfer affects whether or not passengers make their connection. In theory a smaller standard deviation will lead to a greater chance of making the connection and less additional travel time. However, for the 5% standard deviation, additional travel time is greater for tight transfers. As scheduled transfer times get longer (2 minutes in the tram-to-train transfer and 4 minutes in the train-to-tram transfer), the average additional travel time is now less than for 20%. This means that tighter transfers can be more reliable if the first line has a lower standard deviation.

The steeper slope of the 5% standard deviation means that more reliability benefits can be gained as a minute of scheduled travel time is lost.

For the 40% standard deviation, tighter transfers result in less additional travel time in the train-to-tram case. This is because this large standard deviation causes some vehicle to arrive early, making it more likely for passengers to make a transfer that they otherwise would miss.

The restriction on the departure times of the train plays a role in the difference between these two results. When the train is the second vehicle, it can not depart early. This increases the chances of passengers making their connection, meaning that tighter transfers in this direction are more reliable.

Reliability Buffer Time is lower and drops into the make-make distribution at a tighter
Figure 6.8: The effect of varying the standard deviation of a tram line and a train line for transfers from tram-to-train and train-to-tram
transfer for lower standard deviations. The high standard deviation causes more passengers to miss their connection, even at longer transfer times.

6.3.2 Standard deviation of the second line

The standard deviation of the second line affects whether or not a passenger makes their connection, and the distribution of their connection time.

An increased standard deviation generally leads to an increase in additional travel time. In this case the shape of the Additional Travel Time curves are more similar for the three different standard deviations as scheduled transfer times increase. The 5% standard deviation on the second line does not cause Reliability Buffer Time to drop as early as it did on the first line, nor does it cause Additional Travel Time to drop as steeply. In this case the slope of the Additional Travel Time line is not very different whether the standard deviation is increased or decreased.

6.3.3 Conclusions of variation of vehicle operations

As expected, the standard deviation of vehicle running times, an indicator for the amount of variability of vehicle departures and arrivals, plays an important role in passenger reliability for transferring passengers. Here it has been shown that more can be gained from a decrease in standard deviation from the first line than from the second line. This effect is not as stronger when the first line is a tram line because of the operational differences between the tram and train lines.

The variation in travel times can be addressed by the transit operator in order to improve the reliability of the service for passengers. This can be done through a range of operational measures that are outside the scope of this work and by incorporating vehicle holding, which will be discussed in Chapter 7.

6.4 Number of Passengers

It should be fairly clear that the number of passengers in a specific passenger group has an impact on that passenger groups effect on the total network. To demonstrate this, first the effect of varying the schedule of one tram line is shown, and then the effect of varying the schedule of both tram lines. This was done in a hypothetical network with 10 minute headways on all lines.

The hypothetical network is set so that the train schedules depart from the transfer point at the same time in both directions. The tram schedule can be shifted in either direction to set the desired scheduled transfer times. However, setting the transfer time for one transfer has a direct effect on an opposing transfer. For example, if the train-to-tram transfer is set to be short, the tram-to-train transfer has to be long.

As expected, varying the scheduled transfer times of the four transfers has an effect on the system total additional travel time as shown in Figure 6.9.

The optimal point, for least amount of average additional travel time, is shown to be in the same place (7 minutes for transfers A and C, 4 minutes for transfers D and F), regardless of the amount of passengers. This optimal point is shifted in this direction primarily because there is less chance that passengers will miss transfers from the tram to the train (D and F) because the train will not depart early.

Aaron Lee

Master of Science Thesis
6.5 Transfer Walking Time

Transfer walking time, while clearly an important variable, is one that is neglected in this thesis. Changes to and variance in the transfer walking time has not been considered. However it is important to note that the choice for transfer walking time plays an important role in the resulting numbers for scheduled travel time in this thesis. For example, if the transfer walking time was set at 1 minute, instead of 2, the additional travel time and reliability buffer time indicators would each shift by one minute, so that the additional travel time for a 3-minute transfer with 2 minutes of walking time would be the same as that of a 2-minute transfer with 1 minute of walking time.

6.6 Reliability and Scheduled Travel Time

An important trade-off is identified between reliability, made up of additional travel time and reliability buffer time, and scheduled travel time. Previously, it has been noted that an increase in travel time is generally required for an increase in reliability, however depending on the scheduled transfer time and other characteristics, a one minute increase in transfer time may or may not lead to an equal or greater increase in reliability. Figures 6.10 and 6.11 show the sum of scheduled time, additional travel time and reliability buffer time.

In these figures, the top of the average additional travel time curve represents the sum of average travel time per person due to the transfer. For Transfer A, this decreases very slightly between 1 and 4 minute transfer times and then increases the rest of the way. For Transfer D, the decrease is sharper over the tight transfer times, but starts to increase at transfer times above 4 minutes. These graphs can be used to pick the point with the lowest total travel time impact for passengers going through this specific transfer. Here it becomes obvious that gains in reliability offset certain changes in transfer time, but not all.

The top of the reliability buffer time curve represents the impact on total travel time due to the transfer that would be considered by the passenger in order to arrive on time with 95% certainty. For Transfer A, benefits are not reached until an 8 minute transfer time. For
Transfer D (Figure 6.11) this overall impact decreases for scheduled transfer times up to five minutes, and then increases as there are no reliability gains after that point.

The effect on all transfer passengers does not change from the results shown in Figures 6.3 and 6.6, as the average scheduled transfer time evens out. This figure, along with figures for long headways are shown in Appendix B.

6.7 Conclusions and Overview of Results

This section presented the results to several tests, enacted to gain insight into the major variables that impact the reliability of a transfer.

Each of these variables interacts with the scheduled transfer time, the effect of which is one of the main research questions of this research. As expected, a transfer with a greater scheduled transfer time is more reliable. There is a trade-off between scheduled transfer time and reliability. The questions for operators becomes, how small can the scheduled transfer time be, before it becomes unreliable. This chapter has shown that this depends on the headways, operational characteristics and control strategies.

The headways at the transfer have an impact. A shorter headway means the consequences of missing a transfer are fewer, and the acceptable scheduled transfer time could be smaller.

The distributions of the various stochastic processes that make up a transfer have a big impact. What are the arrival and departure distributions of the incoming and departing vehicles? How much walking time is needed to make the transfer.

Of course the number of passengers traveling through a transfer has an impact on the overall effect of a specific transfer in the network. An unreliable transfer with a high amount of passenger traffic has a much bigger overall impact.

When transit operators must synchronize multiple transfers that connect to the same line, they can now choose transfer times that lead to the most overall benefits. A rule of thumb might suggest that the scheduled transfer time should be placed exactly in the middle. However, here is it shown that because of the different control strategies between the tram and the train, that designing the schedule for slightly tighter transfers in the direction of the train has a greater overall benefit.

The main conclusions from the results in this chapter are used as a framework in Chapter 8 in order to assess the possibilities in a case with real data. These main conclusions are also summarized in Table 6.1.
Figure 6.10: Combination of scheduled travel time and reliability for Transfer A with short headways

Figure 6.11: Combination of scheduled travel time and reliability for Transfer D with short headways
<table>
<thead>
<tr>
<th>Cause</th>
<th>Variable</th>
<th>Effect</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>Schedule and network design</td>
<td>Scheduled transfer time</td>
<td>Increased scheduled transfer time leads to increased travel time but a lower probability of missing the transfer</td>
<td>Tighter transfers are less reliable under equal conditions, but the extent of this is dependent on other factors, including the vehicle departure and arrival distributions, control characteristics of the line, and transfer walking times</td>
</tr>
<tr>
<td>Schedule and network design</td>
<td>Headways at transfer</td>
<td>Larger headways increase the magnitude of the negative effect of a missed transfer</td>
<td>The headway of the second vehicle is directly related to the magnitude of additional travel time accrued for any scheduled transfer time</td>
</tr>
<tr>
<td>For Tram: Slack in schedule, distance from terminal to transfer point, location of holding point For Train: Punctuality at transfer point</td>
<td>Variation (standard deviation) of vehicle arrival and departure times</td>
<td>Less variation on one or both lines can increase reliability</td>
<td>Increasing the standard deviation of both vehicles effects reliability, to an extent determined by the scheduled transfer time</td>
</tr>
<tr>
<td>Transfer point layout and behavior of passengers</td>
<td>Transfer walking time</td>
<td>Effects on probability of making a transfer</td>
<td>Less walking time makes smaller scheduled transfer times more reliable</td>
</tr>
<tr>
<td>Demand patterns and quality of service</td>
<td>Percent of transferring passengers</td>
<td>Increases importance of a reliable transfer</td>
<td>More transfer passengers at a specific transfer increases the importance of that transfer</td>
</tr>
</tbody>
</table>

**Table 6.1:** The five main variables with a new results column, showing the results of calculations in a hypothetical network
This chapter describes the effects of adding a schedule based holding strategy at the transfer point. A holding point is intended to narrow the distribution of vehicle departure times at the transfer point, increasing the reliability for transfer passengers. The importance of the width of this distribution was shown in Chapter 6. Holding has traditionally been understood as a trade-off between downstream boarding passengers, who benefit from fewer early departures and through passengers, who accrue additional in-vehicle time while waiting in the held vehicle.

Holding is implemented on both directions of the tram line at the transfer point for the short and long headway networks that were described in Chapter 6. This allows for a comparison of the reliability of the scheduled transfer time with and without holding. It is expected that this holding strategy will benefit passengers transferring from the train to the tram, because there will be less of a chance that they will miss their connecting vehicle.

Because of other line characteristics, it may be beneficial to have a holding point at a different place along the line. A holding point prior to the transfer point will affect passengers transferring to and from the held line. To demonstrate this effect the difference in additional travel time is calculated for a holding point at each of the stops prior to the transfer point.

7.1 Effect of holding at the transfer point

When holding is applied on a line there is a trade-off between the benefit for passengers downstream of the holding point and the extra in-vehicle time for passenger traveling through the holding point. When holding is applied at a transfer point, a new passenger group will be affected: the passengers transferring to the line being held. In theory, holding the vehicle at the transfer will lead to fewer passengers missing their connection and having to wait for the next vehicle.

However, a trade-off exists among the transferring passengers as well. Those who would have missed their vehicle without holding benefit from the holding strategy but those who would have made their intended vehicle with or without holding accrue some extra transfer waiting time while waiting for a vehicle that would have otherwise departed early. Because
of this trade-off, a holding point at a transfer point is beneficial for transferring passengers when there is a higher likelihood of missing the transfer.

Passengers transferring from the held line are not affected in the case that the holding point is at the transfer station because the arrival time of their vehicle does not change.

7.1.1 Effect of holding for short headways

Figure 7.1 shows the effect of holding on transfer passengers of a single transfer for different scheduled transfer times. The shape of the average additional travel time curve is similar to the shape without holding, but with a slightly earlier drop. For longer scheduled transfer times, the holding scenario leads to a higher average additional travel time. This is because for longer scheduled travel times, passengers are much less likely to miss their intended connection. Since the held vehicles do not depart early the average is increased due to lack of contribution from “negative” additional travel times.

The reliability buffer times drop from the Make-Miss travel time distribution to the Make-Make distribution at a shorter scheduled transfer time than in the no-holding case, indicating that a holding point does narrow the distribution of travel times.

Figure 7.2 shows the difference between the holding scenario and the non-holding scenario for all of the effected passenger groups. Transfer A and C passengers, who transfer to the held line, see a reduction in additional travel time at shorter scheduled transfer times, but an increase for longer scheduled transfer times (again because the ‘negative’ additional travel time no longer contributes to the average). The cumulative effect on all direct passengers represents a combination of the reduction in additional travel time from passengers downstream of the holding point and the increase in additional travel time from passengers traveling through the holding point. The change in additional travel time for direct passengers does not depend on the scheduled transfer time, and contributes a net reduction in additional travel time. Holding has a positive effect on transfer passengers, and the entire network, if the scheduled transfer to the holding line is between 2 and 4 minutes.

7.1.2 Effect of holding for long headways

The effects of holding on a long headway system follow a similar pattern to the short headway system. The main differences between the two systems are: 1) the consequence of missing a transfer is greater in a long headway system and 2) travel time distributions are calculated such that passengers can make or miss their first vehicle as well as the transfer. The former does not have an impact in this scenario because the train, as the vehicles on the first leg of the considered transfer do not depart early at any stop and is impossible to miss under the assumptions used in these calculations.

Figure 7.4 shows the effect of holding on transfer passengers for one transfer. The pattern is similar to the short headway case, except the difference between the holding and no-holding scenarios is greater.

Figure 7.5 shows the difference between the holding and non-holding cases for the pertinent passenger groups. Again, the maximum effect on transferring passengers happens when the scheduled transfer time is between 2 and 4 minutes. Here it is clear that the maximum effect from holding is greater in the long headway case than in the short headway case. For the long headways the difference is between 0.5 and 0.6 minutes per passenger, while in the short headway case it is around 0.2 minutes per passenger.

Aaron Lee

Master of Science Thesis
7.1 Effect of holding at the transfer point

Figure 7.1: The effect of a holding point on passengers transferring from Train to Tram for a unique transfer (Transfer A), while varying the scheduled transfer time

Figure 7.2: The difference in average additional travel time of a holding point for the affected passenger groups and the whole system
**Figure 7.3:** Contributions from passenger groups affected by holding to the change in system wide average additional travel time.

**Figure 7.4:** The effect of a holding point on passengers transferring from Train to Tram for a unique transfer (Transfer A), while varying the scheduled transfer time, in long headway conditions.
7.1 Effect of holding at the transfer point

Figure 7.5: The difference in average additional travel time of a holding point for the affected passenger groups and the whole system in long headways conditions.

Figure 7.6: Contributions from passenger groups affected by holding to the change in system wide average additional travel time for long headway conditions.
Figure 7.6 shows that the total benefit accrued by the downstream direct passengers is greater than the total benefit accrued by transferring passengers.

7.2 Holding Point Location

Placing the holding point at the transfer stop has the double advantage that passengers traveling to the held line are less likely to miss their transfer while the passenger traveling from the held line experience no difference in their arrival time at the transfer point. Placing a holding point upstream of a transfer stop may be beneficial for the direct passengers on a line. In addition to narrowing the departure distribution at the transfer point this will narrow the arrival distribution and will skew it so that more vehicles are late rather than early. This has the potential to negatively affect passengers transferring from the held line.

7.2.1 Impact on transfers to the line with holding

This impact was first tested for the scheduled transfer times that are positively affected by holding. The holding point was varied from the beginning of the tram line up to the transfer point for a constant network timetable of 10-minute headways, run over a period of 1200 trips per line. For this case, the scheduled transfer time was chosen to be in the range that demonstrated the most benefit for transferring passengers, a scheduled transfer time of 3 minutes.

Changing the holding point location will, of course affect the original trade-off between downstream passengers and through passengers, but of interest here is the effect on transfer passengers.

![Figure 7.7: Holding point location and it's effect on difference in additional travel time for passengers transferring to a line with holding](image)

Figure 7.7 shows the impact of the location of the holding point on the average additional travel time for passengers transferring to the tram line being held. The two different transfer groups (from each direction of the train) are shown separately, and both demonstrate the same trend. As the holding location moves closer to the transfer stop the benefit from less additional travel time increases.
7.3 Conclusions from holding at a transfer point

A holding point at a transfer stop can reduce the deviation of departure time for the second line of a transfer, and lead to an improvement in reliability for passengers transferring to that line. A holding point at the transfer stop only transfer passengers going to the held line, while a holding point in another location affects other transfer passengers as well.

There is a trade-off within the transferring passengers. Some of them will benefit from the holding point by being able to make a connection that they otherwise would have missed. Others, who would have made the connection anyway, will suffer some additional travel time when having to wait for a vehicle that otherwise would have departed early.

Because of this, a holding point is beneficial when there is a greater chance that passengers will miss their connection, but is actually disbeneficial when the majority of passengers make their connection regardless of the holding regime.

For passengers transferring to a line, a holding point at the transfer point yields the greatest benefit. However, to determine if a holding point is worthwhile, this benefit needs to be evaluated alongside the benefits and costs to the other groups of non-transferring passengers affected by a holding point.

If a holding point is placed before a transfer, it is possible that passengers transferring from the held line will be affected. In this case the trade-off applies between transferring passengers

![Figure 7.8:](image)

**Figure 7.8:** For tight transfers (2 minutes in this case), a holding point applied before the transfer point causes an increase in additional travel time

7.2.2 Impact on transfer from the line with holding

A holding point that is upstream of the transfer station has the impact of narrowing the distribution of arriving vehicles at the transfer point in addition to the distribution of departing vehicles. This adds an additional negative effect on passengers transferring from the lines with holding applied.

This appears in tight transfers from the tram to the train, when the holding point is located before the transfer stop. Figure 7.8 shows the effect of varying the holding point from the beginning of the line until the transfer point. In this case, the transfer time for the impacted transfers is 2 minutes. When the holding point is at stops closer to the transfer point, the negative effect is greater.
downstream of the holding point and transferring passengers upstream of the holding point. Downstream passengers who may have missed their first vehicle, will now make it and can possibly make their transfer. Upstream passengers get delayed by the holding and can possibly miss their transfer. This has the biggest impact when scheduled transfer times are low.

Policy implication: holding is worthwhile for transferring passengers in certain cases. It can be implemented to improve reliability in the case of a tight transfer, although it is not beneficial for longer scheduled transfer times.
In this chapter, the calculation method is applied to an example with real data. The calculation method is designed for real data input and designed to show the passenger costs and benefits of reliability. This application to a real case will demonstrate the possibilities and challenges of the application of this calculation model to a practical problem. The intention of this section is to demonstrate the applicability of the method, not to come to a conclusion on the reliability solution with the most impact.

A two hour period of off-peak evening travel was chosen for this example analysis. Data was filtered for all trips that started at the terminal stop between 20:00 and 22:00. For the seven day period, this led to a total of 56 trips. This is a small sample, but it serves its purpose as an example. The methods and format of the results would be the same for a larger sample. The evening period was chosen because it is the only time of the day when the headways of the train and the tram services are the same. The calculation model can handle uneven headways, but the long-long headway pattern can be compared with the hypothetical cases shown in Chapters 6 and 7.

The following steps are taken from the input of the data to a cost-benefit analysis. Vehicle and passenger data from the HTM and generated train data are used as input, as described in Chapter 5. The scheduled headways of the tram line are not always even, so schedules are adjusted for a regular scheduled headway of the tram at the transfer point. The schedule of each direction of the tram line (Line 1 and Line 2) is then shifted to rotate through the possible scheduled transfer times. Following this, the most reliable point is picked, as judged by Additional Travel Time and Reliability Buffer Time, for a cost-benefit analysis. The difference of the three cost-benefit components, Scheduled Transfer Time, Additional Travel Time and Reliability Buffer Time is shown for each affected passenger group and monetized using the value of time and reliability ratio as shown in Chapter 3.

The output of this chapter is an overview of the cost and benefits to passengers that could be used for a full cost-benefit analysis. Costs to operators are mentioned, but are not detailed. A transit operator looking to use this method would be able to come up with their own cost estimates for changes.
8.1 Analysis of Results

This section presents an analysis of the results of the calculation of Additional Travel Time and Reliability Buffer Time for the example case of the long headway transfer between line 9 in The Hague and the Dutch national rail network at Den Haag HS station. An evening period is used where both services have long headways of 15 minutes. Calculations for long headways are used with the assumptions shown in Chapter 5. For consistency, the transfer walking time is assumed to be 2 minutes with no changes.

First the characteristics of the current situation are examined, then the schedule of each line is shifted in order to find the schedule that provides the most reliable transfers for the combination of different transfer groups.

8.1.1 Current characteristics of the case

Standard Deviations

It was shown in Chapter 6 that standard deviation plays an important role. In this case, the standard deviations at the transfer point (Den Haag HS) are shown in Table 8.1. For the tram lines, the standard deviations at the transfer point, as a percentage of running time, are much less than the 20% that was used in the hypothetical network.

Because the train departures were hypothetically generated, the standard deviation should be the same for each train line, but it is not. This serves as a reminder that this example involves a small sample size.

The 93rd percentiles of departure times show that the generated train schedule is somewhat representative of the Dutch railways, nearly 3 minutes on line 3 and, 1.87 minutes on line 4.

<table>
<thead>
<tr>
<th>Line</th>
<th>Standard Deviation</th>
<th>Trip Time</th>
<th>Percent of Running Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Line 1</td>
<td>1.54 min</td>
<td>24 min</td>
<td>6.4%</td>
</tr>
<tr>
<td>Line 2</td>
<td>1.10 min</td>
<td>16 min</td>
<td>6.9%</td>
</tr>
<tr>
<td>Line 3</td>
<td>1.46 min</td>
<td>20 min</td>
<td>7.3%</td>
</tr>
<tr>
<td>Line 4</td>
<td>0.67 min</td>
<td>20 min</td>
<td>3.4%</td>
</tr>
</tbody>
</table>

Comparison to NS on-time performance

<table>
<thead>
<tr>
<th>93rd Percentile NS</th>
<th>3.00 min</th>
</tr>
</thead>
<tbody>
<tr>
<td>93rd Percentile Line 3</td>
<td>2.94 min</td>
</tr>
<tr>
<td>93rd Percentile Line 4</td>
<td>1.87 min</td>
</tr>
</tbody>
</table>

Table 8.1: Deviation characteristics of the lines in the test case

Current Scheduled Transfer Times

The current scheduled transfer times of each transfer in the evening period for the transfer between Tram line 9 and Den Haag HS are shown in Table 8.2. There is a wide variety of transfer times among the transfers, with some as short as 3 minutes and others as long as 14.

It is assumed that the train schedules remain constant. This represents the likely scenario that the urban operator would be required or encouraged to match their schedule to the train schedule. In the Netherlands, changing the train schedule to match urban operations in one city would be next to impossible because of the complexity of the system.
8.1 Analysis of Results

<table>
<thead>
<tr>
<th>Transfer Name</th>
<th>Scheduled Transfer Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transfer G</td>
<td>3</td>
</tr>
<tr>
<td>Transfer I</td>
<td>12</td>
</tr>
<tr>
<td>Transfer J</td>
<td>5</td>
</tr>
<tr>
<td>Transfer L</td>
<td>14</td>
</tr>
<tr>
<td></td>
<td>Transfers Involving Line 1</td>
</tr>
<tr>
<td>Transfer A</td>
<td>14</td>
</tr>
<tr>
<td>Transfer C</td>
<td>8</td>
</tr>
<tr>
<td>Transfer D</td>
<td>9</td>
</tr>
<tr>
<td>Transfer F</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>Transfers Involving Line 2</td>
</tr>
</tbody>
</table>

Table 8.2: Additional travel time and reliability buffer time for each transfer in the current evening schedule on line 9

<table>
<thead>
<tr>
<th></th>
<th>Original Schedule</th>
<th>Modified Schedule</th>
<th>Tram 2</th>
<th>Tram 2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Depot</td>
<td>Den Haag HS</td>
<td>Headway</td>
<td>Depot</td>
</tr>
<tr>
<td>20:14</td>
<td>20:30</td>
<td>20:14</td>
<td>20:30</td>
<td></td>
</tr>
<tr>
<td>20:29</td>
<td>20:45</td>
<td>20:29</td>
<td>20:45</td>
<td>0:15</td>
</tr>
<tr>
<td>20:44</td>
<td>21:00</td>
<td>20:44</td>
<td>21:00</td>
<td>0:15</td>
</tr>
<tr>
<td>21:12</td>
<td>21:28</td>
<td>21:12</td>
<td>21:30</td>
<td>0:15</td>
</tr>
<tr>
<td>21:42</td>
<td>21:58</td>
<td>21:42</td>
<td>22:00</td>
<td>0:15</td>
</tr>
</tbody>
</table>

Table 8.3: Original and new schedule, designed for uniform headways at the Transfer Point (Den Haag HS)

Shifting the schedule of line 2 will directly affect the transfer times of the first 4 transfers (A,C,D, and E) and shifting the schedule of line 1 will directly affect the transfer times of the second 4 transfers (G,I,J and L.)

Another thing to note, is that the headways are not completely regular over this two hour period. At times a 14 minute headway is scheduled, shifting the scheduled transfer time for some of the vehicles. If synchronization is attempted, it makes sense that a particular transfer is synchronized the same way throughout the time period. In this case, the scheduled headways for line 1 are regular at 15, but the scheduled headways for line 2 are not regular as shown in Table 8.3.

8.1.2 Regularization of headways at transfer point

For the first step, the schedules (and actual departure and arrival times) have been “regularized” so that the transfer times are the same for each vehicle. The departure times of Tram direction 1 have regular 15 minute headways, while the scheduled headways of line 2 are not uniform over the 2 hour period. Changing the departure times from the beginning of line 2, leads to uniform scheduled headways at the transfer point.

The last two columns of Table 8.4 show the effect of this regularization on reliability.
Differences can be seen in two of the transfers relating to line 2 and are particularly prevalent in Transfer F, which had the tightest transfer time.

### 8.1.3 Shifting of the tram schedule

The next step was to shift each of the tram lines separately, to attempt to optimize the four transfer times. The results of these calculations can be seen in Figure 8.1 for line 1 and Figure 8.2 for line 2. The first column of these graphs indicates the original schedule, while the second column indicates the “regularized” schedule and the following columns show the results when the schedule is moved back in time in 1 minute increments.

The reliability of each transfer can be seen for a specific schedule when looking vertically at these charts. For example, shifting line 2 to 5 minutes later than the current schedule leads to a different combination of transfer times and different values for the reliability indicators. Because the train lines do not depart at the same times in both directions (as was used in the hypothetical case), it is difficult to find a time where all transfers are appropriately aligned, so a choice has to be made in order to optimize the schedule for a particular transfer.

In this case, the percentage of passengers going through each transfer was assumed. However, some schedules on the “All Transfer Passengers” graphs have a better overall reliability for transfer passengers than others. For minimum additional travel time and reliability buffer time, Line 2 looks to be in as good of a place as any, although there is room to move. The ideal spot on line 1 involves shifting the line 1 schedule 10 or 11 minutes later (4 to 5 minutes earlier would accomplish the same feat).

### 8.1.4 Conclusion of analysis

This analysis shows that it is difficult to optimize all 4 transfers but an optimal point can be found which minimizes additional travel time and reliability buffer time. For this case, shifting the schedule of line 2 does not lead to increased reliability, as it is already at its most optimal point. Shifting the schedule of “Tram 1” 11 minutes into the future (or 4 minutes back) decreases both additional travel time and reliability buffer time. This shift will be used for an example cost-benefit analysis.
Figure 8.1: The effects on single transfer passenger groups of shifting the line 1 direction of Tram line 9 in Den Haag
Figure 8.2: The effects on single transfer passenger groups of shifting the line 2 direction of Tram line 9 in Den Haag
8.2 Cost-Benefit Analysis

The cost benefit analysis is done for the schedule change of shifting the schedule of “Tram 1” 11 minutes into the future (or 4 minutes back).

8.2.1 Benefits and costs to passenger groups

As shown in Chapter 3. The costs and benefits to passengers are split into three categories: change in scheduled travel time, change in additional travel time and change in the width of the distribution of travel time. For much of this thesis Reliability Buffer Time has been used for the width of the distribution, but standard deviation is the common indicator that is used in practice. This difference plays a big role and can be seen in Appendix D, where full results of the CBA in both cases are displayed. Here, standard deviation is used to be consistent with the values of reliability published by the Dutch Ministry of Infrastructure and the Environment.

<table>
<thead>
<tr>
<th>Change in:</th>
<th>STT</th>
<th>ATT</th>
<th>RBT</th>
<th>Std. Dev.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transfer G</td>
<td>11.0 min</td>
<td>-9.33 min</td>
<td>-0.95 min</td>
<td>-5.27 min</td>
</tr>
<tr>
<td>Transfer I</td>
<td>-4.0 min</td>
<td>0.00 min</td>
<td>0.00 min</td>
<td>0.00 min</td>
</tr>
<tr>
<td>Transfer J</td>
<td>4.0 min</td>
<td>-0.05 min</td>
<td>-0.20 min</td>
<td>-0.17 min</td>
</tr>
<tr>
<td>Transfer L</td>
<td>-11 min</td>
<td>0.51 min</td>
<td>6.16 min</td>
<td>1.27 min</td>
</tr>
</tbody>
</table>

Table 8.5: Changes in scheduled travel time (STT) and reliability (in minutes) for impacted passengers

The difference (in minutes) for these three indicators are shown in Table 8.5. This table shows that the impact of this change in service is a trade-off between change in scheduled transfer time and change in reliability for each transfer. This trade-off primarily exists at two of the transfers: Transfer G becomes more reliable while losing scheduled travel time and Transfer L becomes less reliable while gaining 11 minutes of scheduled travel time.

<table>
<thead>
<tr>
<th>Passengers</th>
<th>Scheduled</th>
<th>ATT</th>
<th>STDev</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transfer G</td>
<td>€-163.58</td>
<td>€138.74</td>
<td>€47.01</td>
<td>€22.17</td>
</tr>
<tr>
<td>Transfer I</td>
<td>€59.48</td>
<td>€0.01</td>
<td>€0.00</td>
<td>€59.50</td>
</tr>
<tr>
<td>Transfer J</td>
<td>€-19.71</td>
<td>€0.26</td>
<td>€0.49</td>
<td>€-18.96</td>
</tr>
<tr>
<td>Transfer L</td>
<td>€54.21</td>
<td>€-2.54</td>
<td>€-3.60</td>
<td>€48.08</td>
</tr>
<tr>
<td>Total (2hr)</td>
<td>€-69.60</td>
<td>€136.48</td>
<td>€43.90</td>
<td>€110.78</td>
</tr>
</tbody>
</table>

Table 8.6: Change in travel time and reliability benefits to passengers

These are monetized, by multiplying by the value of time (10 €/hour) and the reliability ratio (0.6), the number of passengers per transfer and displayed in Table 8.6.

Transfer G matches a substantial loss in scheduled travel time benefit with a gain in reliability. Transfer I realizes a scheduled travel time gain without a loss in reliability. The overall loss in Transfer J and the overall gain in Transfer L come from a change in travel time without a change in reliability. These four changes combine to realize a benefit of €110.78 for the two hour period. This can be translated to a one year period. Assuming these two hours are changed for every weeknight, the total gain is €28802.80.
Nearly 40% of the benefit comes from the standard deviation term for the width of the distribution. This is a significant contribution.

### 8.2.2 Costs to Operators

The methods described in this thesis are intended to demonstrate the travel time change and reliability benefits for a scheduling change. The method does not give any insights to the costs of the scheduling change to operators as this may depend on the situation. However, for this example, an attempt is made to estimate the possible costs to the transit provider.

Possible costs to operators in this scenario could include: deployment of an extra vehicle, cost to employees for change in layover time, extra staff hours and costs associated with interaction with other vehicles along the line.

The effect on operations of this shift deals with the way that recovery time is allocated in the schedule. The effect on process times is shown in Table 8.7. The major impact is a 4-minute change in terminal time. This could have cost implications for the operator, depending on a wide range of factors.

<table>
<thead>
<tr>
<th></th>
<th>Original Case</th>
<th>New Case</th>
</tr>
</thead>
<tbody>
<tr>
<td>Running Time Dir. 1</td>
<td>41 min</td>
<td>41 min</td>
</tr>
<tr>
<td>Turnaround Time</td>
<td>6 min</td>
<td>10 min</td>
</tr>
<tr>
<td>Running Time Dir. 2</td>
<td>40 min</td>
<td>40 min</td>
</tr>
<tr>
<td>Terminal Time</td>
<td>19 min</td>
<td>15 min</td>
</tr>
<tr>
<td>Total Cycle Time</td>
<td>105 min</td>
<td>105 min</td>
</tr>
</tbody>
</table>

*Table 8.7:* Process times for the evening tram schedule on line 9 in Den Haag for the current case and the new case where the schedule of the line 1 direction is shifted.

Assuming that the cost implication to the operator is 4 minutes of additional operating time, because the vehicle is “out of its home” for 4 additional minutes, in every cycle. The cost to the operator can be calculated as shown in Table 8.8, for different potential operating costs. This is done for the 2-hour period, so the total amount of time cost is 32 minutes.

<table>
<thead>
<tr>
<th>Operating Cost of Time</th>
<th>Time used</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>200 €/hour</td>
<td>32 min</td>
<td>106.67 €</td>
</tr>
<tr>
<td>150 €/hour</td>
<td>32 min</td>
<td>80.00 €</td>
</tr>
<tr>
<td>100 €/hour</td>
<td>32 min</td>
<td>53.33 €</td>
</tr>
<tr>
<td>50 €/hour</td>
<td>32 min</td>
<td>26.67 €</td>
</tr>
</tbody>
</table>

*Table 8.8:* Operating costs for a two-hour period.

For this case it is assumed that the cost to operators is purely hourly, with no additional kilometer, vehicle or infrastructure costs. New revenue is also not considered.

The train operator assumes no costs in this scenario as their service does not change. In this example, one operator is responsible for making a change that benefits passengers that use services provided by both operators. This could result in an increase in ridership for both operators, meaning that the national rail network could see revenue benefits without an investment. This is, however, not a blanket generalization, but the outcome of the assumptions made for this example, that the urban transit operator would be expected to make changes to their schedule.
8.2.3 Cost-Benefit Ratio

Combining the passenger benefits and operator costs leads to a benefit-cost ratio. Possible benefit-cost ratios are listed in Table 8.9. This case proves to be slightly beneficial even if the costs are as high as €200 per hour.

This benefit-cost ratio has been obtained from a limited process and should be understood as such. In practice, a number of scheduling changes might be analyzed together in order to cover a bigger portion of the day or a bigger portion of the network.

<table>
<thead>
<tr>
<th>Operating Cost of Time</th>
<th>Passenger Benefit</th>
<th>Operator Cost</th>
<th>Benefit/Cost Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>200 €/hour</td>
<td>€110.78</td>
<td>106.67 €</td>
<td>1.04</td>
</tr>
<tr>
<td>150 €/hour</td>
<td>€110.78</td>
<td>80.00 €</td>
<td>1.38</td>
</tr>
<tr>
<td>100 €/hour</td>
<td>€110.78</td>
<td>53.33 €</td>
<td>2.08</td>
</tr>
<tr>
<td>50 €/hour</td>
<td>€110.78</td>
<td>26.67 €</td>
<td>4.15</td>
</tr>
</tbody>
</table>

Table 8.9: Benefit-cost ratios for the example case

8.3 Conclusions for real data example

The method for calculating reliability for transfer passengers from Automatic Vehicle Locater data has been applied to a small example using real data from the HTM network in The Hague, Netherlands. Despite the small sample, the impact if varying the scheduled transfer times was consistent with what was seen in the hypothetical network.

Based on the analysis of scheduled transfer times, an optimal point was picked and a brief cost benefit analysis was performed to demonstrate the impact of the change in reliability.

It was demonstrated that there is an overall benefit to the passengers for this particular shift in the schedule, however the cost to the operator is uncertain. It is possible that this improvement could be made without direct costs, however the change in departure time from the terminal may be operationally challenging due to procedures at the terminal as well as the possibility of mixed tram traffic on shared portions of the line. There are many intangible factors that could make this shift disbeneficial to the operator.

Passenger costs and benefits are a trade-off between transfer groups, scheduled transfer time and reliability. Each group that was affected by the schedule changes in this example experienced this balance to some extent.

It is complicated to optimize synchronization for all of the transfers at a transfer point. The case described in this example is simple compared to the reality at the Den Haag HS station, which includes as many as 5 tram lines that can connect with the train. It is unlikely that all transfers could be scheduled for maximum reliability, so there will always be some sort of trade-off.
Chapter 9

Conclusion and Recommendations

This thesis has examined the effects of reliability on passengers and operators for a multi-level public transit network with two separate operators. A method was developed to calculate Additional Travel Time and Reliability Buffer Time for transferring passengers.

The main objectives of this thesis were (1) to extend the Additional Travel Time calculation model in Van Oort (2011) to account for passengers traveling through a transfer point, (2) to test two tactical reliability improvement measures in a network situation and identify the impacts on the various passenger groups and (3) to identify the costs and benefits for each operator associated with these improvement measures. Through this an understanding was gained of the main variables that impact reliability at a transfer point.

**Five variables that impact transfer reliability for passengers**

In Chapter 4 and Chapter 6, the five variables that impact reliability for transferring passengers were identified. They are: arrival and departure distributions of vehicles on both lines, headways of both lines, transfer walking time and scheduled transfer time. The major impact of these variables is that they can cause passengers to make or miss their intended transfer. Passengers missing a transfer is the biggest contributor to more unreliable wider travel time distributions and higher Additional Travel Time.

**Impact of the scheduled transfer time on reliability for transfer passengers**

It was shown in Chapter 4 that the impact of scheduled transfer time depends on the other variables. In general a shorter transfer time is less reliable. While a longer transfer time is more reliable, a trade-off exists as lengthening the scheduled transfer time also lengthens the scheduled travel time.

An important dynamic is that shifting the transfer time of one transfer, changes the transfer time of at least one opposing transfer. The point where both transfers are reliable lies somewhere in the middle and depends on the characteristics of the services.

The consequence of missing a transfer is greater in longer headway services. It was shown that scheduling for increased reliability will require choices to be made that depend on the characteristics of both lines, including the variability of vehicle operations and the control regime of the line. Tighter transfers are more reliable when a control strategy is applied, as in
the case with the train, where the second vehicle does not leave early. In the cases shown here, when balancing the two transfers between the same two lines, scheduling less transfer time for the tram-to-train transfer has more overall reliability benefits than scheduling a transfer right in the middle. However, specific cases should be tested with data that is relevant to those situations.

**Impacts and trade-offs for reliability when a holding strategy is applied**

Applying a holding point can have an impact on the arrival and departure distribution of vehicles at a transfer point. As an important variable, this change can impact reliability.

With the consideration of transfer passengers, an additional trade-off was added to the traditional holding trade-off between downstream passengers and passengers traveling through the holding point. The impact of holding on transfer passengers depends on the scheduled transfer time. For longer scheduled transfer times, adding a holding point at the transfer point produced a negative effect on transfer passengers. For shorter scheduled transfer times a holding point increased reliability. This highlights a trade-off among transferring passengers. Holding is beneficial for passengers that would have missed their connection if not for a holding point, however it is not beneficial for passengers who would have made their connection anyway. These passengers essentially join the through passengers in sitting in a waiting vehicle. Holding is disbeneficial for long transfer times with a lower probability of passengers missing their connection, but is beneficial for shorter transfer times. In this case holding can be applied as an alternative to shifting the schedule, or when it is impossible to shift the schedule for external reasons.

A holding point that is placed prior to the transfer station has an affect on passengers transferring to and from the held line. This scenario will narrow the distribution of departures at the transfer point, but not to the same extent as when the holding point is placed at the transfer point. However, for passengers transferring from this line, their average arrival at the transfer point will be slightly more delayed, giving them more of a chance of missing their transfer. These phenomena apply to tighter transfer times, but are not applicable in the case of longer transfer times.

**Impacts to the costs and benefits to passengers and operators**

Reliability in a network is a complex issue. What is reliable for one group of passengers may not be reliable for another group. Shifting one transfer directly changes one to three additional transfers. Adding a holding point can impact direct passengers as well as transferring passengers. While the effects on reliability of shifting the transfer time may look impressive for a single passenger group, the overall network effect is much less.

Chapter 8 showed the procedure for using the calculation method to determine the costs and benefits to passenger groups in a brief example with real data. Here it was shown that the costs and benefits to passengers come from combination of changes to scheduled travel time, additional travel time and reliability buffer time. Benefits gained from reliability are offset by costs in scheduled transfer time.

Costs for the reliability improvement measures in this thesis can be difficult to determine, because they do not necessarily directly lead to one of the traditional public transit cost indicators: number of vehicles, distance traveled, or operational hours. However, this thesis provides a framework for determining the costs and benefits to passengers. An operator who
is willing to make a change should have a more accurate cost estimate at their disposal.

In the case of two separate operators, a benefit to transferring passengers is actually a benefit to passengers who are patrons of both services. It has been shown that a change in the urban transit schedule can benefit transferring passengers, who also happen to be train passengers. Here, to some extent, train passengers are benefiting without any costs associated to the train operator. This could result in an increase in ridership and revenues. Here, there is a case for urban and regional operators to work together and communicate when there is the possibility of increasing reliability for transferring passengers.

9.1 Takeaways for transit operators, governments, transportation professionals and laypeople

Transit operators should be aware that reliability is an important component of the service they provide and that transfers should not be neglected. Reliability analysis done for a single line fails to consider the impacts of the service to passengers whose trip consists of multiple stages.

An urban transit operator may be required to connect their service to a regional rail service. In many cases, passengers will be transferring from an urban vehicle to the train, while train passengers will be transferring to that same urban vehicle. This work has shown that that it is possible to schedule the transfer in this case for the maximum possible reliability. For even headways and different control conditions, it may be more beneficial to set the urban transit schedule to be somewhere other than exactly in the middle of the regional rail schedule.

Governments should consider reliability in their analysis of public transportation improvement projects. However, they should do so knowing that a fairly wide range of values of reliability have been suggested in the scientific community. While standard deviation is generally used to measure reliability, as the width of the travel time distribution, there are other measures including Reliability Buffer Time, which could better describe a passenger’s value of reliability. Currently adding the reliability term to a cost-benefit analysis appears to have a significant effect, but implementation must be done in a way such that there is consistency in the cost-benefit analysis process.

Public transit reliability could be considered in a public transit assignment model by adding terms for the magnitude and width of the distribution of travel time (ATT and RBT) for each public transit trip. More research needs to be done to implement this so that models can better describe public transit passenger behavior and choices. Transportation professionals should encourage further study on reliability in public transit with the aim of being able to successfully incorporate it into transportation models and cost-benefit analyses.

Laypeople can hope that their transit vehicles are running on time today. An unreliable transit service is something that is a part of everyday life for many people throughout the world. A smooth connection, or a vehicle arriving just when you want it can have a wonderfully positive impact on an individual’s life experience. While data is aggregated to optimize for a system and is spoken about in averages and other big-picture terms, operators, governments and transportation professionals should not forget that the impact eventually is felt by an individual.

Master of Science Thesis
Aaron Lee
9.2 Recommendations for further research

This research has presented a broad look at the reliability of a transfer point and has identified several areas that should be given closer attention. The improvement measures of scheduled transfer time and holding both feature intricacies and could be given more specific attention. Further attention should be placed on the context of reliability for modeling and cost-benefit analysis.

Reliability Buffer Time was shown to be quite sensitive, especially in the case of transfers where the passengers travel time is really a distribution made up of two separate distributions. Its principle is sound, but it is possible that it works better in certain contexts than others. These contexts should be studied. Further research is needed to know if Reliability Buffer Time appropriate to use in a cost-benefit analysis or as a variable in a public transit assignment model, or if is it simply an indicator that tells something about the passenger’s experience.

Research should continue surrounding the implementation of reliability in cost benefit analysis. More work is needed on the value of reliability in order to converge on some generally accepted values. Statistics other than standard deviation should be investigated as an indicator of the width of the distribution. In a brief result here, a huge difference is seen between using reliability buffer time and standard deviation.
Appendix A

Comparison of similar transfers

Figures A.1 and A.2 show that transfers from the tram to the train and vice versa behave in the same way as each other in the hypothetical network. Therefore one transfer can be used to represent behavior of a typical train-tram or tram-train transfer.

Figure A.1: Comparison of additional travel time and reliability buffer time for the 4 transfers from train-to-tram

Figure A.2: Comparison of additional travel time and reliability buffer time for the 4 transfers from tram-to-train

Master of Science Thesis Aaron Lee
Appendix B

Scheduled Time and Reliability Long Headways

Figure B.1: Combination of scheduled travel time and reliability for Transfer A with long headways
Figure B.2: Combination of scheduled travel time and reliability for Transfer D with long headways.

Figure B.3: Combination of scheduled travel time and reliability for all transfer passengers with long headways.
Appendix C

Sensitivity analysis for number of passengers in CBA case

This is a brief sensitivity analysis for the assumption in Chapter 8 that 50% of transferring passengers are sent in each direction. Figures C.1 and C.2 show the effects of changing the assumption for the number of transferring passengers. The original assumption was that all passengers boarding or alighting the tram at the transfer point were transferring from or to the train. Because there are two possible train directions, passengers were split with 50% going each way. Here the same shifting of line 1 and line 2 are performed with transfer passenger splits of 80% and 20%. First with 80% of passengers allocated to transfers A, D, G and J and second with 80% of passengers to transfers C, F, I and L.

It should be noted that the individual average additional travel times for each transfer do not change at all, but their importance in the average additional travel time for all transferring passengers changes, thus affecting this average.

The effect of changing the direction of the transferring passengers can be seen clearly when looking at the base case. Under the original assumption, with a 50-50 split, passengers average 2.75 minutes of additional travel time. With 80% of the passengers in one direction (A,D,G,J) resulted in an average of 3.86 minutes of additional travel time, a 40% increase. With 80% of passengers going the other direction (C,F,I,L) resulted in 1.59 minutes of additional travel time, a 42% decrease.

When shifting the scheduled departure times of line 1 and line 2, the overall most reliable points for all transferring passengers did not change in either case. However, the least reliable points did change, especially when shifting the schedule of line 1. While there were two equally unreliable points in the original passenger distributions, one of them (a 3 minute shift) became more unreliable under the 80-20 scenario while the other (a 12 minute shift) became more unreliable under the 20-80 scenario.
Sensitivity analysis for number of passengers in CBA case

Figure C.1: Sensitivity of number of transfer passengers for all transfers while shifting the schedule of Tram direction 1

Figure C.2: Sensitivity of number of transfer passengers for all transfers while shifting the schedule of Tram direction 2
Appendix D

Cost Benefit Analyses

This appendix presents two analyses of the benefits and costs to passengers based on the reliability improvement of shifting the schedule of one tram line 11 minutes into the future. For these number is it important to note:

1. negative numbers indicate negative total costs, and thus benefits
2. Figure D.1 uses 95th percentile – 50th percentile RBT for the value of the width of the distribution
3. Figure D.2 uses standard deviation of the travel time distributions for the value of the width of the distribution
4. The number of passengers given represent the two hour period that was used for analysis

Chapter 3 details some of the differences between the two methods and the reasons for using them.
### Costs and Benefits for Passenger Groups: 25% of Time from 6 am till 6 pm in the evening hours

<table>
<thead>
<tr>
<th>Passenger Group</th>
<th>Travel Time</th>
<th>Average Change</th>
<th>Value of Time (€)</th>
<th>New Value per Passenger</th>
<th>Reliability Ratio</th>
<th>Weighted Value per Passenger</th>
<th>No. of Passengers</th>
<th>Total Cost (€)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scheduled Time</td>
<td>0.00</td>
<td>0.17</td>
<td>-</td>
<td>3 €</td>
<td>1.00</td>
<td>-</td>
<td>21,615</td>
<td>-</td>
</tr>
<tr>
<td>Additional Time</td>
<td>0.00</td>
<td>0.17</td>
<td>1</td>
<td>3 €</td>
<td>1.00</td>
<td>-</td>
<td>21,615</td>
<td>-</td>
</tr>
<tr>
<td>Reliability Buffer Time</td>
<td>0.00</td>
<td>0.17</td>
<td>0.00</td>
<td>3 €</td>
<td>1.00</td>
<td>-</td>
<td>21,615</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

| Additional Travel Time | 0.00 | 0.17 | - | 3 € | 1.00 | - | 21,615 |
| Reliability Buffer Time | 0.00 | 0.17 | 0.00 | 3 € | 1.00 | - | 21,615 |
| Total               | 0.00 | 0.17 | 0.00 | 3 € | 1.00 | - | 21,615 |

| Scheduled Time | 0.00 | 0.17 | - | 3 € | 1.00 | - | 21,615 |
| Additional Time | 0.00 | 0.17 | 1 | 3 € | 1.00 | - | 21,615 |
| Reliability Buffer Time | 0.00 | 0.17 | 0.00 | 3 € | 1.00 | - | 21,615 |
| Total               | 0.00 | 0.17 | 0.00 | 3 € | 1.00 | - | 21,615 |

| Scheduled Time | 0.00 | 0.17 | - | 3 € | 1.00 | - | 21,615 |
| Additional Time | 0.00 | 0.17 | 1 | 3 € | 1.00 | - | 21,615 |
| Reliability Buffer Time | 0.00 | 0.17 | 0.00 | 3 € | 1.00 | - | 21,615 |
| Total               | 0.00 | 0.17 | 0.00 | 3 € | 1.00 | - | 21,615 |

| Scheduled Time | 0.00 | 0.17 | - | 3 € | 1.00 | - | 21,615 |
| Additional Time | 0.00 | 0.17 | 1 | 3 € | 1.00 | - | 21,615 |
| Reliability Buffer Time | 0.00 | 0.17 | 0.00 | 3 € | 1.00 | - | 21,615 |
| Total               | 0.00 | 0.17 | 0.00 | 3 € | 1.00 | - | 21,615 |

| Scheduled Time | 0.00 | 0.17 | - | 3 € | 1.00 | - | 21,615 |
| Additional Time | 0.00 | 0.17 | 1 | 3 € | 1.00 | - | 21,615 |
| Reliability Buffer Time | 0.00 | 0.17 | 0.00 | 3 € | 1.00 | - | 21,615 |
| Total               | 0.00 | 0.17 | 0.00 | 3 € | 1.00 | - | 21,615 |

| Scheduled Time | 0.00 | 0.17 | - | 3 € | 1.00 | - | 21,615 |
| Additional Time | 0.00 | 0.17 | 1 | 3 € | 1.00 | - | 21,615 |
| Reliability Buffer Time | 0.00 | 0.17 | 0.00 | 3 € | 1.00 | - | 21,615 |
| Total               | 0.00 | 0.17 | 0.00 | 3 € | 1.00 | - | 21,615 |

### Figure D.1: Travel time costs and benefits, using reliability buffer time
Fig. D.2: The framework used for the calculation of additional travel time and reliability buffer time depending on the network characteristics and passenger types.


