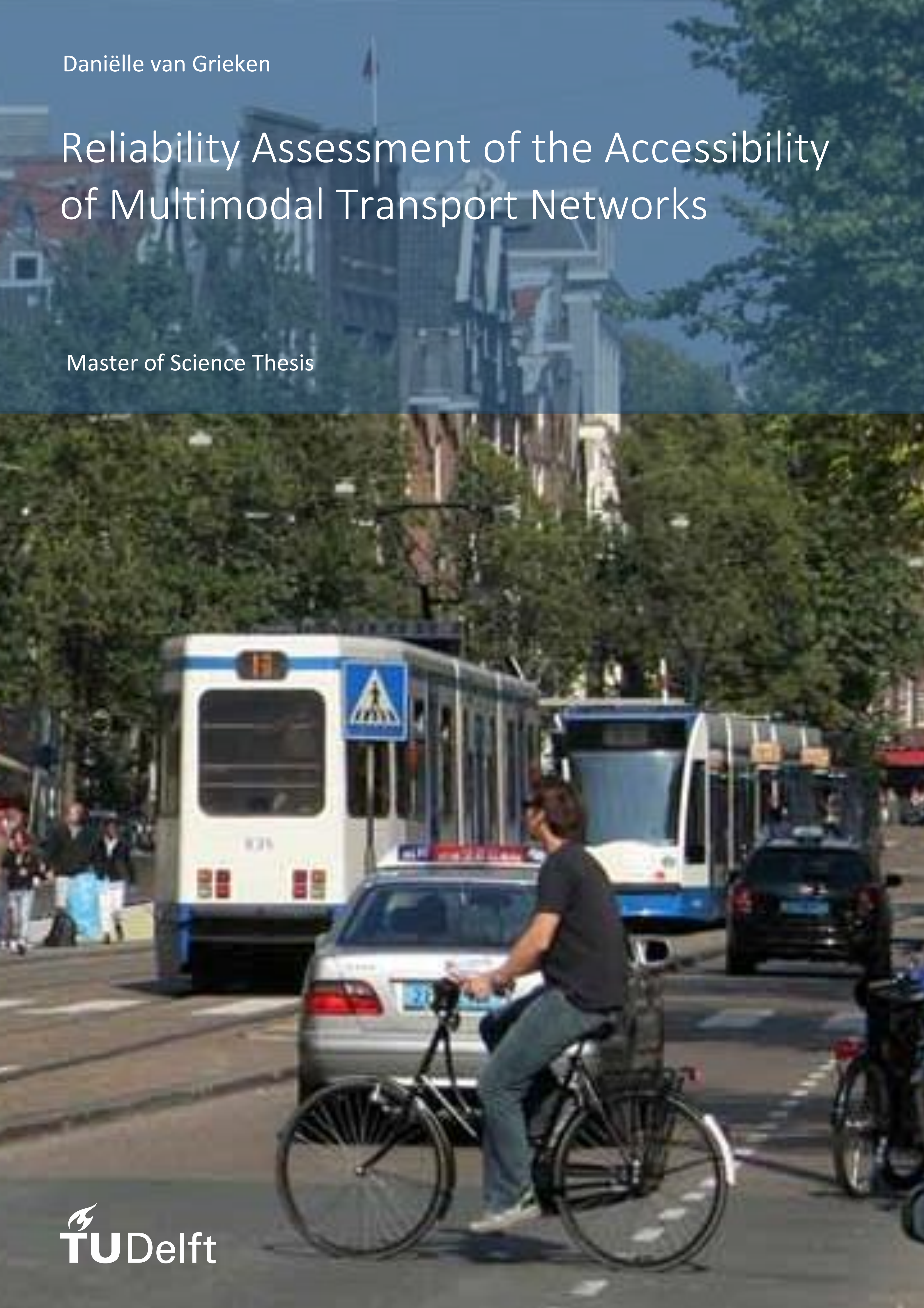
Daniëlle van Grieken

Reliability Assessment of the Accessibility of Multimodal Transport Networks

Master of Science Thesis



TU Delft

Reliability Assessment of the Accessibility of Multimodal Transport Networks

D. van Grieken

October 31, 2017

Master Thesis Report

in partial fulfilment of the requirements for the degree of

Master of Science
in Civil Engineering

at the Delft University of Technology,
faculty of Civil Engineering, department of Transport & Planning.

Graduation committee Civil Engineering, track Transport & Planning		
Chairman	Prof.dr.ir. B. van Arem	Delft University of Technology
Daily Supervisors	Dr.ir. R. van Nes Dr. M. Snelder	Delft University of Technology TNO
External supervisor	Dr. J.A. Annema	Delft University of Technology

Executive Summary

Introduction

Authorities at all levels agree that it is important to maintain a good accessibility and a reliable transport system. Accessibility is defined as “the ease with which an area can be reached”. A reliable transport system means a transport system that performs at an accepted level during a given period of time. Over the last few years, authorities have begun to view the transport system from a user perspective in which the transport networks of the separate modes are merely components that make up the total transport system. From a user perspective, the availability of multiple (equivalent) modes could be seen as a benefit, as it gives them the option to choose which mode they would like to use. Also, in case of disruptions of one of the modes, it enables them to choose another option, which ensures they can still make the trip. This provides a more reliable trip than when those alternatives are not available for consideration. This line of thought implies that the reliability of the network improves when multiple (equivalent) modes are considered. However, practice shows that a reliability assessment for the total multimodal network doesn’t exist yet.

In current transport network evaluations, the reliability is assessed using a single travel time of a single route of a single mode and is determined for a specific departure time (or time period in which the departures take place) at a specific network level. Networks can be assessed on (*link level*,) *route level* or *location/zonal level*. For a single time point, the result will be expressed in travel times or accessibility. Including multiple time points gives the possibility to evaluate the route on travel time reliability and the locations on reliability of accessibility. This is schematically presented in .

Table 0.1 Overview of different network levels & assessments

	(Link or) Route level	Location/zonal level
Single time point	Travel Times	Accessibility
Multiple time points	Travel Time Reliability	Reliability of Accessibility

When assessing a transport network, conventionally only one mode and one route are considered. However, in reality a traveller will have multiple modes (e.g. car, public transit, bicycling, walking) available and multiple route options for each mode available. For a more accurate representation of the available alternatives of a traveller, these options need to be considered (given in).

Table 0.2 Mode & route options in transport network evaluations

	Considered modes	Considered routes	Explanatory Notes
1.	Single mode	Single route	Basic form; only 1 mode per network is considered and 1 route per mode is considered.
2.	Single mode	Multiple routes	One mode is considered per transport network, with multiple routes per mode. The thesis of (de Boer, 2014) studies this for the road network.
3.	Multiple modes	Single route	A network with multiple modes and a single route per mode are assessed. A comparison between modes can be made and the combination of having multiple modes available. Is the focus of this research.
4.	Multiple modes	Multiple routes	A network consisting of multiple modes, with multiple routes per mode is considered. This basically combines the previous two options together.

The goal of this research is to develop an assessment method for the reliability of travel times (on a route level) and the reliability of accessibility (on a zonal level) when single unimodal routes with alternatives over multiple modes are considered.

The main research question derived from this, is formulated as:

> *How can the reliability of travel times (on a route level) and the reliability of accessibility (on a zonal level) be assessed when single unimodal routes with alternatives over multiple modes are considered?*

Reliability, Accessibility & Aggregation Methods

A (literature) study is performed into the (existing) methods to determine the reliability, the accessibility and existing aggregation methods to include multiple alternatives.

Reliability

Reliability has been the subject of many studies. Over time, different types of reliability have been distinguished (Chen et al., 2002; Clark & Watling, 2005): *connectivity reliability, capacity reliability*, *behavioural reliability*, *potential reliability* and t*ravel time reliability*. This thesis focusses on travel time reliability.

Reliability indicators are (re)searched and described. For this research, a small number of indicators are selected to be used. The selected indicators are given in , along with their formulas and a short description.

Table 0.3 Reliability indicator selected for this research

Measure	Formula	Description
Average; Mean (μ)	$\mu = \frac{\sum_{n=1}^{N} TT_n}{n}$	
Standard Deviation ($STD; \sigma$)	$\sigma = \sqrt{\frac{1}{N-1}\sum_{N}(TT_n - \mu)^2}$	The variation in travel time compared to the mean/average.
Coefficient of Variation ($COV; c_v$)	$c_v = \frac{\sigma}{\mu}$	The ratio between the standard deviation and the mean.

Accessibility

The term accessibility is generally defined by “the ease with which an area can be reached”. An extensive evaluation of existing accessibility indicators was found in an article by (Geurs & van Wee, 2004). In the current thesis, two accessibility indicators were used:

1. Hansen’s Potential Value (Hansen, 1959);
2. SVIR Accessibility Indicator (Ministerie van Infrastructuur & Milieu, 2012).

These indicators are chosen because they determine accessibility in a different way: Hansen’s Potential Value measure is used to determine an ‘active accessibility’ as the Potential Value is calculated based on the potential locations which can be reached. The SVIR Accessibility Indicator is used to determine a ‘passive accessibility’, as this is calculated based on how good this location can be reached from other locations. All indicators use a travel time to calculate the accessibility.

Aggregation methods

For the accessibility over multiple modes, a value needs to be selected that can be used as the travel time. Simplest thing would be to use one of the modes (fastest travel time, fastest free flow time or highest utility as used in Discrete Choice Analysis), however, that doesn't capture the additional value of having the set of alternatives available. Thus an aggregation method is needed that captures this additional value.

The most theoretically accurate aggregation method is found in the Logsum method as introduced by (Ben-Akiva & Lerman, 1985), which is related to the Discrete Choice Analysis:

$$V'_{od,agg,t} = \frac{1}{\mu} \ln \sum_{m} e^{\mu V_{od,m,t}}$$

In which:

$V'_{od,agg,t}$ = The maximum (=aggregated) utility between origin o and destination d at time t [-]
$V_{od,m,t}$ = The utility function between origin o and destination d for mode m at time t [-]
μ = scale parameter of the logit model [-]

If the utility function $V_{od,m,t}$ is expressed in travel times only, the Logsum ($V'_{od,agg,t}$) is also expressed in travel times. However, if the alternatives are represented by different modes, mode choice plays an important role and the aggregation is not so straightforward anymore, as the sensitivities for the travel times and the Alternative Specific Constants differ per mode. This is addressed in the next section.

Aggregation over multiple modes

The aggregation method as introduced by (Ben-Akiva & Lerman, 1985) is rewritten so that alternatives over multiple modes can be considered:

$$V'_{od,agg,t} = \frac{1}{\mu} \ln \sum_{m} e^{\mu\left(ASC_m + \beta_m * TT_{od,m,t}\right)}$$

In which:

$V'_{od,agg,t}$ = The aggregated utility between origin o and destination d at time t [-]
$TT_{od,m,t}$ = The travel time between origin o and destination d of mode m at time t [min]
ASC_m = The Alternative Specific Constant of mode m [-]
β_m = The sensitivity parameter for mode m [1/min]
μ = scale parameter of the logit model [-]

This "aggregated utility" (Logsum) is rewritten to an "aggregated travel time" so that it can be used to calculate the accessibility, where the parameters β_{LS} and $ASC_{LS} = ASC_{m|ASC=0} = 0$ are used to reverse-engineer the travel time from the Logsum:

$$TT'_{od,agg,t} = \frac{1}{\beta_{LS}} \left(\ln \sum_{m} e^{\left(ASC_m + \beta_m * TT_{od,m,t}\right)} \right)$$

The Logsum is now expressed solely in a travel time, but is still also influenced by the sensitivity β_m of the mode with $ASC_m = 0$. To obtain a generic absolute travel time, the parameter β_{LS} should then be equal to the β_m of that same mode for consistency reasons. To ensure that the aggregated travel time is smaller than the minimum travel time, the value of $\beta_{LS} = \beta_m$ should be equal to the highest absolute value of β_m. As the Logsum will be equal or smaller than the minimum utility, the differences between the aggregated travel time and the minimum travel time will be limited.

For the determination of the travel time reliability and the reliability of the accessibility, the previously described indicators can be used. Two situations can be distinguished:

- "Reliability within a Day"
- "Reliability over Days"

To be able to calculate both situations, travel times for multiple time points and multiple days need to be collected over multiple modes.

Case Study

To illustrate the practical application of the above mentioned theory, a case study was conducted for the city of Amsterdam. Eight locations were selected, between which the travel times were collected over multiple modes for multiple time points (in total 88 time points per day and 33 days) using the Google Maps Distance Matrix API (Google Developers, 2017).

The travel time reliability was determined for each of the 56 OD-relations with the previously described reliability indicators. Furthermore, the accessibility for each of the locations was calculated before the reliability of the accessibility was determined (shown in Figure A.2).

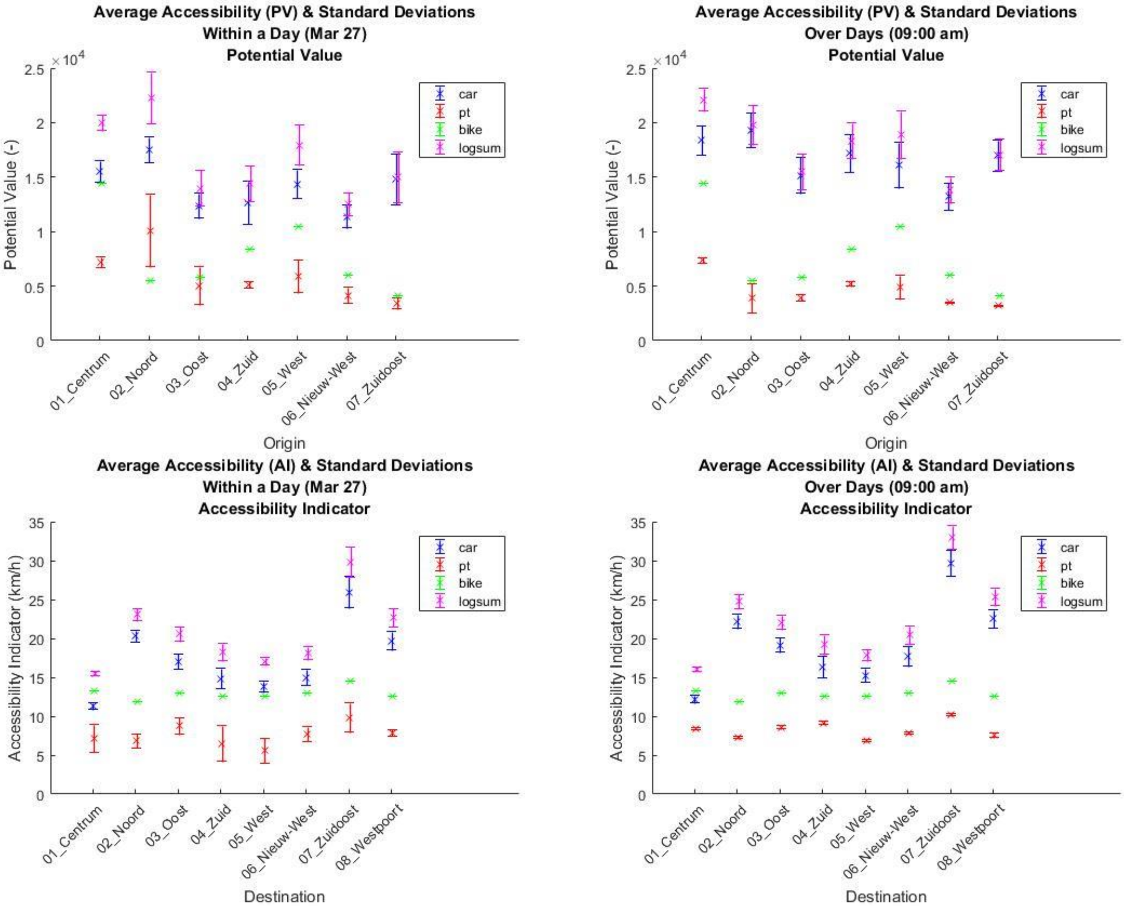


Figure 0.1 Results: Reliabilty of the Accessibility (top: Potential Value, botom: SVIR Accessibility Indicator) within days (left) and over days (right)

The case study shows that the Logsum method (also in the rewritten form of the aggregated travel time) always gives results that are equal or better than the fastest mode. The difference between the Logsum and the individual modes represents the additional value a traveller experiences for having multiple alternatives available. It also becomes clear that, based solely on travel times, public transport is not an attractive alternative.

Considering multiple modes provides insight in the reliability of a mode in comparison to other modes. It shows for which mode improvements are most needed. Aggregation over modes gives one value for each OD-relation/location, which could be compared amongst each other though is very reliant on the spatial characteristics.

The reliability within a day shows larger deviations than the reliability within a day, indicating that the departure time is of large influence for the expected travel time. As a reliable travel time is desired at all moments of the day, the reliability within a day is more useful than the reliability over days. The latter can be used as an extension of the former.

By calculating the reliability of both travel times and accessibility, the reliability can be given at the desired level of aggregation. For a quick analysis of the whole city, the reliability of the accessibility can be consulted. For extra insight in the travel times from or to a certain location, the travel time reliability can be examined for the OD-relations originating in or going to this location.

Conclusions

In conclusion, this research has examined how the travel time reliability and the reliability of the accessibility over multiple modes could be determined. The travel time reliability and the reliability of the accessibility was determined with the Average (μ), the Standard Deviation (σ) and the Variation Coefficient (c_v) for two situations: 'Reliability within a day' and 'Reliability over days'.

As reliable travel times are desired at all moments of the day, the 'Reliability within a day' provides a better picture of the reliability than the 'Reliability over days'. The 'Reliability over days' can be used as an extension of the 'Reliability within a day' to provide additional insight in unreliable travel times.

To determine the reliability over multiple modes, the Logsum method is used as a basis for the "aggregated travel time over multiple modes", which combines the travel times of multiple modes into one value. The Logsum method gives a suitable foundation for this provided that the values for the parameters β_{LS} and ASC_{LS} were equal to the parameters of the mode with $ASC_m = 0$ and the highest (numeric) value for β_m.

Table of Contents

Executive Summary 4

Table of Contents 9

1 Introduction 11

- 1.1 Problem description 11
  - 1.1.1 Current Transport Network Evaluations 12
  - 1.1.2 Network Aggregation Levels 12
  - 1.1.3 Modes and Routes in a Network 12
- 1.2 Objective & Research Questions 13
- 1.3 Overview of the Report 14

2 Reliability, Accessibility & Aggregation Methods 15

- 2.1 Reliability 15
  - 2.1.1 Definitions of Reliability 15
  - 2.1.2 (Travel Time) Reliability Indicators 16
  - 2.1.3 Reliability Indicators used in this Research 18
- 2.2 Accessibility 18
  - 2.2.1 Definitions of Accessibility 18
  - 2.2.2 Accessibility Indicators 19
  - 2.2.3 Accessibility Indicators used in this Research 20
- 2.3 Aggregation Methods 22
  - 2.3.1 Simple Aggregation Methods 22
  - 2.3.2 Discrete Choice Analysis 22
  - 2.3.3 Logsum method 24
- 2.4 Summary Reliability, Accessibility & Aggregation Methods 24

3 Aggregation over Multiple Modes 26

- 3.1 Aggregation of Travel Times over Multiple Modes 26
- 3.2 Reliability 27
  - 3.2.1 Reliability of Travel Times 27
  - 3.2.2 Accessibility & Reliability of the Accessibility 28
  - 3.2.3 Data Collection Method 28
- 3.3 Summary Aggregation over Multiple Modes 29

4 Case Study Amsterdam 30

- 4.1 Setup Case Study Amsterdam 30
  - 4.1.1 Classification of location and OD-relations 31

4.1.2 Google Maps Distance Matrix API 32
4.1.3 Collected Data 33
4.1.4 Quality of Collected Data 35
4.2 Data Processing 36
4.2.1 Aggregation of Travel Times over Multiple Modalities 36
4.2.2 Travel Time Reliability 37
4.2.3 Reliability of the Accessibility 37
4.3 Results 38
4.3.1 Travel Time Reliability within a Day 38
4.3.2 Travel Time Reliability over Days 43
4.3.3 Reliability of the Accessibility within a Day 47
4.3.4 Reliability of the Accessibility over Days 51
4.4 Conclusions Case Study 54
4.4.1 Application of Theory 54
4.4.2 Data Collection 55
4.4.3 Amsterdam 55
5 Conclusions & Recommendations 57
5.1 Conclusions 57
5.1.1 Answers to the Sub Research Questions 57
5.1.2 Answer to the Main Research Question 60
5.1.3 Conclusions Case Study 60
5.2 Recommendations 61
6 References 62
A Travel Time Distributions 64
B Quality of Collected Public Transit Data 67
C Choice for Utility Function in Case Study 70

1 Introduction

With the growing population, the increasing amount of travelled distance and public space gradually becoming scarcer, mobility is an important topic in national, regional and local policies. All authorities agree that the mobility and the accessibility of their regions need to be maintained and ensured, now and in the future.

At several political levels authorities have stated as such. The Ministry of Infrastructure and the Environment has stated in the National Policy Strategy for Infrastructure and Spatial Planning (Ministerie van Infrastructuur en Milieu, 2012) that: "[…] accessibility (in terms of the effort, expressed in time and costs per kilometre, that users have to make to travel from door to door) is currently inadequate. A robust and comprehensive mobility system will feature multimodal hubs, offer more choice and have sufficient capacity to deal with projected increases in mobility in the medium (2028) and longer term (2040)".

On a regional scale, the provinces and municipalities of and around Amsterdam have initiated informally the Amsterdam Metropolitan Area (Metropoolregio Amsterdam, 2016). The MRA has stated in the Spatial-Economic Action Agenda for 2016-2020 (Metropoolregio Amsterdam, 2016) that the cooperating municipalities plan to facilitate travel in, from and to the area and they aim to improve the urban accessibility, all the while making better use of the current space, services, infrastructure and qualities before making new investments and extensions.

Likewise, the Mobility Approach of the municipality of Amsterdam (Gemeente Amsterdam, 2013) sketches how to keep Amsterdam accessible in the future as well. By making better use of the current transport capacity and giving priority to cost efficient and space saving transport modes the municipality aims to find an answer to the question how, with less resources and limited space, the city hopes to find solutions for the growing mobility demand.

1.1 Problem description

While authorities over all levels agree that it is important to maintain a good accessibility and a reliable transport system, practice shows that in the past governments have usually focused on solving bottlenecks in the separate transport systems, because a reliability assessment method for the multimodal network as a whole does not yet exist.

More and more authorities are starting to view the transport system from a user perspective. This results in an outlook in which the transport networks of the separate modes are merely components of the total transport system. From a user perspective, the availability of multiple (equivalent) modes could be seen as a benefit, as it gives them the option to choose which mode they would like to use. Moreover, in case of disruptions in one of the networks, it enables the users to choose another option, which ensures they can still make the trip (provided that there is enough spare capacity of course). This provides more reliability than when those alternatives are not available for consideration. Following this line of thought implies that the reliability of the network might improve when multiple (equivalent) modes can be considered.

However, most transport evaluation assessments have not caught up yet and often the transport networks are still evaluated separately. In the paragraph below it is further discussed how network are currently evaluated.

1.1.1 Current Transport Network Evaluations

In current transport network evaluations it is assessed to what extent the (current) transport network satisfies the desired level of reliability given the current transport demand. The current assessment method uses a single travel time of a single route of a single mode and is determined for a specific departure time (or time period in which the departures take place) at a specific network level.

This departure time could be a specific time point at a specific day, but it could also consist of a time period including several time points in a day or several time points over multiple days. With the network level the level at which the network is viewed is indicated (e.g. at a link level, a route level or a location/zonal level). The section 'Network Aggregation Levels' will continue on this.

For each mode, a separate network is considered: the car network, public transport network, bicycle network and pedestrian network exist alongside each other, but are evaluated separately. Public transport is in this case a collective term for all shared-passenger services such as train, metro, tram, bus, etc. While it could be argued that these services each have their own network (e.g. a separate train network can be distinguished, as well as a metro network, tram network, bus network, etc.), in this thesis all these services will be considered together as one 'public transport network'.

When assessing the reliability of the multimodal transport network as a whole, it is desirable to consider these separate transport networks together. In each network multiple routes between an origin and a destination can be distinguished, although these routes are not always taken into account. This is explored below in the section 'Modes and Routes in a Network'.

1.1.2 Network Aggregation Levels

A transport network can be evaluated at three different aggregation levels. When viewing and assessing a specific segment or bottleneck of a network, we say that the network is evaluated at *link level*. When aggregating multiple segments/links and a whole route between an origin and a location is assessed, the network is evaluated at *route level*. Aggregating multiple routes over an origin or destination, the network is assessed on a *location* or *zonal level*.

When evaluating a transport network at a specific departure time (single time point) on the link or route level, only the network performance can be expressed in average conditions such as speeds, travel times or generalized costs. On a location/zonal level this performance will be expressed in accessibility.

Including multiple time points, gives the possibility to evaluate the network on reliability as well. When assessing a network on link or route level, this means that the reliability of travel times can be assessed. On location/zonal level, this would be called the reliability of the accessibility. This is schematically presented in Table 1.1. In this thesis, only assessment on route level and location level will be included.

Table 1.1 Overview of different aggregation levels & assessments

	Link level	Link & Route level	Location/zonal level
Single time point	Travel Times	Travel Times	Accessibility
Multiple time points	Travel Time Reliability	Travel Time Reliability	Reliability of Accessibility

1.1.3 Modes and Routes in a Network

When assessing a transport network, conventionally only one mode and one route are considered. However, in reality a traveller will have multiple modes (e.g. car, public transit, bicycling, walking) available and multiple route options for each mode available. For a more accurate representation of the available transport networks of a traveller, these options need to be considered. This results in the possible transport networks given in Table 1.2.

Table 1.2 Mode & route options in transport network evaluations

	Considered modes	Considered routes	Explanatory Notes
1.	Single mode	Single route	Basic form; only 1 mode per network is considered and 1 route per mode is considered.
2.	Single mode	Multiple routes	One mode is considered per transport network, with multiple routes per mode. The thesis of (de Boer, 2014) studies this for the road network.
3.	Multiple modes	Single route	A network with multiple modes and a single route per mode are assessed. A comparison between modes can be made and the combination of having multiple modes available. Is the focus of this research.
4.	Multiple modes	Multiple routes	A network consisting of multiple modes, with multiple routes per mode is considered. This basically combines the previous two options together.

In the past, each network was often considered with only a single mode and a single route. In the past years, research has been done into the aggregation of multiple routes in the road network (de Boer, 2014). The current thesis develops a method to include multiple modes where one route per mode is considered. Furthermore, the impact of reliability is considered as well. If successful, this could be combined to include multiple routes and multiple modes into one network.

All modes are considered unimodal trips (even the multimodal public transport trips). For the future, these options could also be expanded with adding multimodal trips (i.e. adding transfer between two public transit modes or between one mode and another).

1.2 Objective & Research Questions

This research aims to include multiple modes into existing travel time reliability assessment methods and to extend existing reliability and accessibility assessment methods with the inclusion of the reliability of the accessibility. For this research, single unimodal routes will be considered. This leads to the objective as described below.

Goal

To develop an assessment method for the reliability of travel times (on a route level) and the reliability of accessibility (on a zonal level) when single unimodal routes with alternatives over multiple modes are considered.

From the previously described goal, the research questions can be derived. These will be presented below. One main research question is constructed as well as multiple sub research questions, which are clustered by the themes reliability, (reliability of) accessibility, the aggregation of alternatives over multiple modes and data collection at multiple time points.

Main Research Question

How can the reliability of travel times (on a route level) and the reliability of accessibility (on a zonal level) be assessed when single unimodal routes with alternatives over multiple modes are considered?

Sub Research Questions

- *Reliability*
    - *How can the reliability of travel times (on a route level) be determined?*
- *(Reliability of) Accessibility*
    - *How can the accessibility (on a zonal level) be determined?*
    - *How can the reliability of the accessibility (on a zonal level) be determined?*
- *Aggregation of alternatives over multiple modes*
    - *Which aggregation methods can be used to aggregate travel times of alternatives over multiple modes?*
- *Data collection at multiple time points*
    - *Which data source(s) can be used to collect travel times for multiple modes at multiple time points?*
    - *What are the possibilities & limitations of these data sources?*

To answer the research questions, first a literature study is performed to learn more about reliability, accessibility and (existing) aggregation methods. Then selection of the indicators and methods will take place. Lastly, a case study is conducted for assessing the feasibility of the proposed assessment method and the implications for practice.

1.3 Overview of the Report

In this section the structure of this thesis will be described. In order to find an answer to the research questions described in the previous paragraph, the definitions and indicators for reliability and accessibility as found in literature are given in chapter 2, as well as different aggregation methods. Also, in this chapter the choice will be made and elaborated which indicators and methods will be used in the remainder of this research.

In chapter 3 the aggregation method will be extended over multiple modes. Furthermore, this chapter will further explain on the methodology which was used to determine the travel time reliability and the reliability of accessibility. Also, the requirements of the data will be given at the end of this chapter.

Chapter 4 consists of the practical application of the previously proposed methodology, which starts with the data collection method that was used. Then, the travel times were collected between the origins and destinations consisting of 8 locations. The reliability of these travel times and the reliability of the accessibility of these 8 locations were then determined.

Finally, in chapter 5 the conclusions and recommendations will be given as found for this research. The answers to the research questions will also be summarized in this chapter.

2 Reliability, Accessibility & Aggregation Methods

This chapter addresses the current developments which can be found in literature and practice concerning the topics which have the key focus of this study: reliability, accessibility and the inclusion of multimodality in these two topics.

First, different definitions of reliability will be explored before (relevant) indicators for (travel time) reliability will be given (section 2.1). For accessibility (section 2.2), the same setup will be followed: first different definitions will be given before different indicators are explored. In paragraph 2.1.3 and paragraph 2.2.3, the indicators for the reliability and the accessibility respectively that will be used during this research will be chosen and elaborated on.

For the inclusion of multiple modes in the reliability and accessibility indicators, several aggregation methods for travel times will be explored in the last section of this chapter (section 2.3).

2.1 Reliability

Apart from travel time, reliability is often used to determine the “quality of a transport network”. In literature, several definitions can be found for reliability, which will be elaborated in paragraph 2.1.1. In paragraph 2.1.2 indicators for (travel time) reliability will be given and elaborated on. Last, in paragraph 2.1.3 the indicators which will be used in the remainder of this research will be chosen.

2.1.1 Definitions of Reliability

Many studies have been done into the reliability of networks. According to Immers, et al. (2011) the “most generally accepted definition of reliability” is given by (Billington & Allan, 1992) and (Wakabayashi & Iida, 1992):

> *Reliability is the probability of a network performing at its proposed service level adequately for the period of time intended under the operating conditions encountered.*

Over time, different types of reliability have been distinguished by some authors (e.g. Chen et al., 2002), which (Clark & Watling, 2005) have identified as classes of reliability:

- *Connectivity reliability* is concerned with the probability that network nodes remain connected, whereby each link of a network is assumed to have an independent, probabilistic, binary mode of operation which can be open/closed or can more generally reflect on a more subjective definition of the successful function of a link. The objective of this method is to compute the probability that a particular route or movement between an origin and destination is connected, or more generally will function as desired. This method is especially suitable for events in abnormal situations like natural disasters (or extreme incidents) and is also referred to as robustness.
- *Capacity reliability* considers the probability that the network can accommodate a certain traffic demand at a required service level. (Introduced in (Chen, et al., 2002).)
- *Behavioural reliability* considers an effect on mean network performance, which is presumed to arise from the modified, average behaviour of drivers in their attitude to the unpredictable variation and/or the perceived risks. The issue is how to represent (in an equilibrium

framework) the impact on the typical route choice pattern or on other responses like departure time choice.

- *Potential reliability* aims to identify potential weak points/problems and their effect(s). In this context, several methods can be found which propose measures to determine network vulnerability such as a robustness analysis framework (Snelder et al., 2012) or an identification of vulnerable links in the network (Knoop et al., 2012). It is noted that potential reliability has a strong relation with what in the Netherlands would be called robustness (Snelder et al., 2014).
- *Travel time reliability* considers the probability that a trip can be made within a specified time interval (Immers, et al., 2011), whereby an assessment of route travel times (derived from route travel times) is made. For the user of the network, route travel time is most informative (compared to capacity, occupancy, flow, etc.).

Travel time reliability can be viewed as the most expressive and easiest communicated reliability class. The research in this thesis will focus on travel time reliability and indicators for this will therefore be elaborated below.

2.1.2 (Travel Time) Reliability Indicators

Travel time reliability is typically expressed using performance indicators based on travel time distributions. In current research several techniques can be found, which can be divided into the following categories (Lomax et al., 2003; van Lint et al., 2008):

- *Statistical Range Measures*
- *Buffer Time Measures*
- *Tardy Trip Indicators*

Statistical Range Measures typically use standard deviation statistics to present an estimate of the range of expected travel times in the form of average travel time plus/minus a factor times the standard deviation on a given time of day (TOD), day of the week (DOW) period. This implicitly assumes travel times to be symmetrically (e.g. normally) distributed. However, with a reference to (van Lint & van Zuylen, 2005) it can be said that “a symmetrical distribution probably only exists in the case of – trivial – time periods in which just free-flow conditions occur”.

Buffer Time Measures indicate the effect of unusual circumstances in the form of the amount of extra time that travellers should take into account to still achieve their destination in time in a high percentage of the situations. The *Buffer Time Index* indicates the percentage extra travel time which travellers should take into account to still arrive on time in either 90% (or sometimes 95%) of the time, compared to the average on a given time of day (TOD), day of the week (DOW) period. The *Planning Time Index* (PI) expresses the extra time a traveller should take into account in addition to the free-flow travel time to arrive on time in 95% of the time.

Tardy Trip Indicators describe the travel time unreliability using the amount of trips that result in (unacceptably) late arrivals. The *Misery Index* (MI) calculates the (relative) difference between the mean travel time of the 20% worst trips and the mean travel time of all travellers on a given time of day (TOD), day of the week (DOW) period.

These indicators, along with a few additional ones found in reliability reports of (SHRP2), were also found in in a TNO report of 2014 (Snelder, Calvert, & Minderhoud, 2014). The indicators, along with their formulas are given in Table 2.1. For a visual representation (and easier interpretation) of these indicators, they can be added to a travel time distribution as shown in Figure 2.1.

Table 2.1 Summary of "classical" travel time reliability measures as presented by (van Lint et al., 2008) & in (Snelder, Calvert, & Minderhoud, 2014), based on (SHRP2)

Category	Measure	Formula	Description
Statistical Range	Average; Mean (μ)	$\mu = \frac{\sum_{n=1}^{N} TT_n}{n}$	
	Standard Deviation ($STD; \sigma$)	$\sigma = \sqrt{\frac{1}{N-1}\sum_{N}(TT_n - \mu)^2}$	The variation in travel time compared to the mean/average
	Semi-Standard Deviation	$\sqrt{\frac{1}{N}\sum_{n=1}^{N}\left(TT_n - TT_{ff}\right)^2}$	The variation in travel time compared to the free flow travel time
	Coefficient of Variation ($COV; c_v$)	$c_v = \frac{\sigma}{\mu}$	The ratio between the standard deviation and the mean
Buffer Time	Buffer Time Index (BI)	$BI = \frac{TT_{90\%} - \mu}{\mu}$	The extra time required to arrive at a destination on time 90% of the time, compared to the mean travel time
	Planning Time Index (PI)	$PI = \frac{TT_{90\%}}{TT_{ff}}$	The extra time required to arrive at a destination on time in 90% of the time
Tardy Trip	Misery Index (MI)	$MI = \frac{\mu\vert_{TT_n > TT_{80\%}} - \mu}{\mu}$	How much longer it takes to travel on the worst 5 percent of all trips

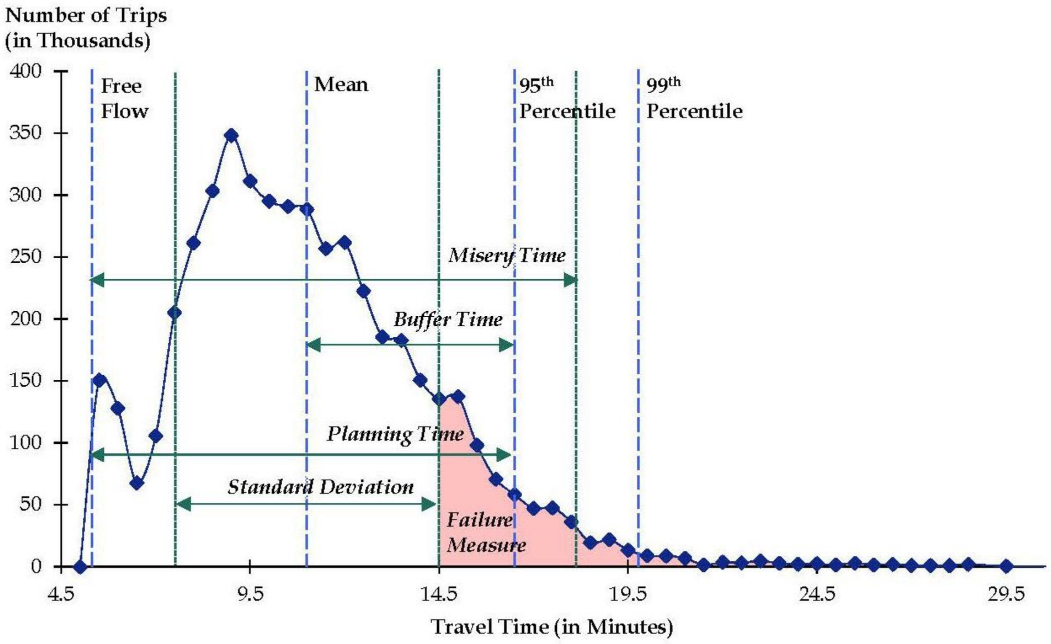


Figure 2.1 Travel Time Distribution as a basis for defining reliability measures (SHRP2, 2014)

In practice, many variations of the above mentioned indicators are used. All measures describe a different part of the travel time distribution, therefore all measures have their own added value. It depends on what a researcher or policy maker is interested in, which indicators are most useful.

2.1.3 Reliability Indicators used in this Research

For this research it is decided to use a small number of indicators, so as to keep the method relatively simple and straightforward. The reliability indicators that were selected are:

- Average (μ)
- Standard Deviation (σ)
- Variation Coefficient (c_v)

First, the Average and Standard Deviation were selected to be used as reliability indicators. Besides the easy interpretation, the Standard Deviation can also be monetary evaluated with a Value of Reliability (although this is not carried out in this research). Additionally, the Variation Coefficient was selected which standardizes the travel times based on the average travel time, so that the length of the trip becomes of less influence.

In order to use these indicators, data with the following characteristics is needed:

- **Travel time of observation n (TT_n):** all travel times of all observations are needed.
- **The number of observations N:** the total number of observations is needed to calculate the mean/average.

2.2 Accessibility

In this section, the (theoretical) definitions and indicators for Accessibility will be elaborated. In paragraph 2.1.1 the theory and several definitions will be given. In paragraph 2.1.2 different indicators for accessibility will be given, while in paragraph 2.1.3 a selection out of these indicators will be made, which indicators will be used in the rest of this research.

2.2.1 Definitions of Accessibility

Accessibility is often an important indicator for policy makers. Generally speaking, it can be defined by: “the ease with which an area can be reached”. An extensive evaluation of existing accessibility indicators can be found in an overview by (Geurs & van Wee, 2004). In this article, four (types of) components of accessibility are identified (land-use, transportation, temporal and individual) as well as four perspectives on measuring accessibility (infrastructure-based, location-based, person-based and utility-based). Then, the usefulness and limitations of existing accessibility measures are evaluated on the following criteria: theoretical basis, operationalization, interpretability & communicability and the usability in social & economic evaluations. The article states that ideally, “an accessibility measure should be sensitive to changes in the quality of transport services (transport component), the amount and distribution of the supply of and demand for opportunities (land-use component) and temporal constraints (temporal component). It should also take individual needs, preferences and abilities into account (individual component).” However, it is also stated that applying all of these criteria would require a level of complexity and detail that can probably never be achieved in practice. Different situations and study purposes require different approaches in practice. It is important to observe the implications of ignoring one or more of these criteria.

It is concluded that infrastructure-based accessibility measures, such as average speed like in the accessibility indicator as defined by the Dutch ministry (which will be elaborated in the paragraph ‘SVIR Accessibility Indicator’ in paragraph 2.2.3), are easy to interpret but lack the land-use component, and temporal and individual elements. More complex location- and utility-based overcome the most important shortcomings and can be considered effective accessibility measures. The lack of individuals’ spatial-temporal constraints, which are typically included in person-based accessibility measures, remains an important theoretical shortcoming. Person-based measures have the potential to be very useful for social evaluations, but still have considerable disadvantages related to data availability and complexity, which restricts the use of these measures to relatively small regions and subsets of the population.

2.2.2 Accessibility Indicators

Indicators which determine the accessibility of an area have been in use for a long time and are used by decision makers to substantiate the choices that need to be made. As mentioned in the article by (Geurs & van Wee, 2004) and elaborated in the previous section, the following distinction can be made in accessibility measures:

- Infrastructure-based accessibility measures;
- Locations-based accessibility measures;
- Person-based accessibility measures;
- Utility-based accessibility measures.

Infrastructure-based accessibility measures are used to describe the (observed or simulated) performance or service level of transport infrastructure, such as ‘travel times’, ‘level of congestion’ and ‘operating speed on the road network’. An example of an infrastructure-based accessibility indicator is the ‘Accessibility Indicator’ as commissioned by the Dutch Ministry (described in paragraph 2.2.3).

Location-based accessibility measures can be further divided in the following groups: *distance and contour*, *potential measures* and *balancing factors of spatial interaction*. *Distance measures* (also called *connectivity measures*) are the simplest of location-based accessibility measures, e.g. the ‘relative accessibility’ as proposed by (Ingram, 1971). The most simple measure of relative accessibility is the straight line between two points, but infrastructure-based accessibility measures like average travel times and average speed between two locations can also fall under this category. If more than two possible destinations are analyzed, a *contour measure* is acquired. *Potential accessibility measures* (also called *gravity-based measures*) estimate the accessibility of opportunities in an origin zone i to all other zones (n) in which smaller and/or more distant opportunities provide diminishing influences. The measure is generally of the following form, with the cost function assuming a negative exponential form:

$$A_i = \sum_{j=1}^{n} D_j \, e^{-\beta c_{ij}} \tag{2.1}$$

In which A_i is a measure of accessibility in zone i to all opportunities D in zone j, c_{ij} the costs of travel between zone i and zone j, and β the cost sensitivity parameter. The cost sensitivity function has a significant influence on the outcome of such accessibility measures and should therefore be carefully chosen. Hansen’s Potential Value measure (Hansen, 1959) is one of the best-known potential accessibility measures, and will be further elaborated below. Lastly, the *balancing factors* as proposed by (Wilson, 1970; Wilson, 1971) in his double constrained spatial interaction model can be interpreted as accessibility measures. The balancing factors have the following form:

$$a_i = \sum_{j=1}^{n} \frac{1}{b_j} D_j \, e^{-\beta c_{ij}} \tag{2.2}$$

$$b_j = \sum_{i=1}^{m} \frac{1}{a_i} O_i \, e^{-\beta c_{ij}} \tag{2.3}$$

In which the balancing factors a_i and b_j ensure that the magnitude of the trips originating at zone i and destined at zone j equals the number of activitity in zones i (e.g. workers) and j (e.g. jobs).

Person-based accessibility measures analyse accessibility from the viewpoint of individual incorporating spatial and temporal constraints and are founded in the space-time geography of (Hägerstrand, 1970). Although these accessibility measures have great theoretical advantages and these approaches seem to have a fast growing interest in travel behaviour research, the application in accessibility studies is relatively rare due to the necessary data that is often not available.

Lastly, *Utility-based accessibility measures* interpret accessibility as the outcome of a set of transport choices. Utility theory addresses the decision to choose one discrete option from a set of potential alternatives, all of which satisfy essentially the same need and can be used to model travel behaviour and the benefits of different users of a transport system. Two types of this measure are used in literature. The first is based on random utility theory using the Logsum as an accessibility measure. In this case, the Logsum is used to indicate the desirability of the full choice set. In our research, this measure will be examined as an aggregation method in paragraph 2.3.3 where it will further be elaborated. The second is based on the double constrained entropy model, though this is not applicable for this research and will therefore not be further elaborated.

2.2.3 Accessibility Indicators used in this Research

In this research, it was decided to limit the number of accessibility indicators which are taken into account. Only two measures have been included at the end:

1. The Potential Value measure as described by (Hansen, 1959);
2. The Accessibility Indicator as devised by the (Ministerie van Infrastructuur & Milieu, 2012).

First, the Potential Value measure was chosen because of its advantages: due to its simple equation and ease to calculate and implement. Furthermore, potential accessibility measures like this are suitable to be used in social and economic evaluations, as mentioned by (Geurs & van Wee, 2004) though this has not been relevant in this research. Disadvantages of these gravity-based measures, as they are also called, are the difficulty with which the measure can be interpreted and communicated as well as the lack of competition effects and temporal restrictions. The Potential Value is one of the widely used location-based accessibility measures, which are considered to be effective measures of accessibility as concluded by (Geurs & van Wee, 2004). The equation for this indicator will be further elaborated below.

From a practical viewpoint, the SVIR Accessibility Indicator was chosen as the second accessibility indicator. As it has been constructed (or at least was commissioned) by the Dutch government, it is reasoned that this will often be a preferred accessibility measure by Dutch authorities. The equation for this indicator will be elaborated below.

It is noted that these indicators approach accessibility from different perspective. Hansen's Potential Value indicator calculates the accessibility starting from the origin points, so the potential locations what can be reached, which can be viewed as 'active accessibility'. The SVIR Accessibility Indicator calculates the accessibility from the perspective of the destination points, so as how good this location is accessible from other locations, which can be viewed as 'passive accessibility'.

Hansen's Potential Value

As described before, the Potential Value measure is the first of the two accessibility indicators which will be used in this research. First introduced by Hansen (1959), the potential value of a location is used as a measure to define the accessibility of a location. The potential value of a location is the sum of all clients/jobs/etc. which can be reached within a certain distance/time of that location:

$$PV_i = \sum_j M_j * f(C_{ij}) \tag{2.4}$$

With:

$$f(C_{ij}) = \frac{1}{c_{ij}^b} \tag{2.5}$$

In which:

M_j = Mass of destination zone j (for instance the number of inhabitants or the number of jobs)
$f(C_{ij})$ = Cost function of the travel between origin zone i to destination zone j
c_{ij}^b = Costs between origin zone i to destination zone j to the power b

In order to use this formula for the accessibility, data needs to be collected with the following characteristics:

- **Mass of the destination zone *j*:** for example, this could be the number of inhabitants or the number of available jobs in this particular zone. In this case, the number of inhabitants will be used (or possibly the number of inhabitants who are interested in taking the trip).
- **Costs:** this can be expressed in travel time, travel costs, distance, utility or generalized costs, for example.

SVIR Accessibility Indicator

In the national policy strategy (Ministerie van Infrastructuur & Milieu, 2012) of the Dutch government, "Accessibility" is defined as "the effort it takes users from door to door to reach their destination". The policy strategy introduces an accessibility indicator ('Bereikbaarheidsindicator' or 'BBI' for short in Dutch), which is further explained in the report "De SVIR bereikbaarheidsindicator" (Ministerie van Infrastructuur en Milieu, 2014). The SVIR Accessibility Indicator gives per transport mode the average speed (km/h) for all door to door movements from all origins to one destination:

$$AI_j = 1/\frac{\sum_{i=1}^{I} P_{ij} * TT_{ij}}{\sum_{i=1}^{I} P_{ij} * d_{ij}} \tag{2.6}$$

In which:

AI_j = SVIR accessibility indicator of destination zone j
I = Total number of origins
P_{ij} = The number of movements between origin zone i to destination zone j
TT_{ij} = The travel time between origin zone i to destination zone j
d_{ij} = The distance between origin zone i to destination zone j

To use this formula, the following data is needed:

- **The number of trips/movements between each origin zone i and each destination zone j:** the number of movements between two zones for each mode is needed.
- **Travel time between each origin zone i and each destination zone j:** for each origin-destination pair the travel time for each mode is needed.
- **Distance between each origin zone i and each destination zone j:** the direct distance between two zones.

It is noteworthy that by using the number of movements, this method calculates the accessibility by the given what is reached, not by the potential what might be reached (therefore 'passive accessibility'). Furthermore, the SVIR accessibility indicator focusses on the accessibility of destination zones and calculates the accessibility for each modality separately (for instance: car, train and bus/tram/metro or car, public transit & bike) in a uniform manner.

2.3 Aggregation Methods

As seen in the previous paragraph, both (travel time) reliability indicators and (most) accessibility indicators use travel times as input to determine the (travel time) reliability and the accessibility. In order to use these indicators for the reliability assessment of a multimodal network, it is necessary to aggregate the travel times of the different modes to a single representative value. In this section, different aggregation methods are examined and explained.

2.3.1 Simple Aggregation Methods

The simplest aggregation methods which can be distinguished are those that pick one of the available modes. Three possibilities can be distinguished:

- The travel time of the fastest mode is chosen;
- The mode with the fastest free flow travel time is chosen;
- The average of the travel times over the modes is chosen;
- The mode with the highest utility is chosen.

In the simplest option, the travel times of the different modes are compared, before the mode with the lowest travel time is chosen. In the second case, the same steps are followed, only now the free flow travel times are compared, meaning the travel times without delays are regarded. Thirdly, the In the last case, the travel times of the separate modes are used to calculate an 'utility', before the mode with the highest utility is chosen. Calculating the utilities falls actually under the Discrete Choice Analysis, so this will be further explained in the next paragraph.

2.3.2 Discrete Choice Analysis

Discrete Choice Modelling contains the theory and application of describing, explaining and predicting choices between two or more discrete alternatives. The choice for an alternative is made based on the utility of that mode. The utility function $U_{od,m,t}$ can be expressed in a systematic or representative component ($V_{od,m,t}$) and a random component ($\varepsilon_{od,m,t}$), also called disturbances (Ben-Akiva & Lerman, 1985):

$$U_{od,m,t} = V_{od,m,t} + \varepsilon_{od,m,t} \tag{2.7}$$

With:

$V_{od,m,t}$ = the systematic (or representative) component of the utility [-]
$\varepsilon_{od,m,t}$ = the random parts of the utility, also called disturbances [-]

In the most simple form, only the travel times are used as input variable to determine the utility ($V_{od,m,t}$) in the abovementioned formula. In that case all other reasons why a choice would be made are modelled by parameters:

- The travel time can be multiplied by a parameter β, which expresses the sensitivity of the travel time (of a decision maker / traveller).
- All other factors that are of influence for a decision maker when choosing an alternative but not included/specified in the utility function, are expressed by the Alternative Specific Constant (parameter ASC). The ASC_m expresses the (relative) preference of a decision maker for a specific alternative/mode. Since this is a relative preference of a decision maker for one alternative compared to the other alternatives, one of the alternatives will be neutral and have an $ASC = 0$.

These parameters could be either absent, fixed or mode dependent. However, not having a β and a fixed ASC will not give distinctive utility functions. The (feasible) options are given in Table 2.2.

Table 2.2 Possibilities to include parameters with resulting utility functions

		ASC	
		No ASC	Mode-dependent ASC
β	Fixed β	$\beta * TT_{od,m,t}$	$ASC_m + \beta * TT_{od,m,t}$
	Mode dependent β	$\beta_m * TT_{od,m,t}$	$ASC_m + \beta_m * TT_{od,m,t}$

In literature, many more complex options can be found for utility functions. For instance, often the utility function will include a cost-component and/or dummy variables to include personal characteristics of the decision maker/traveller. However, since travel time and travel cost are often related to each other, it is decided to exclude travel costs in the function. Furthermore, personal characteristics of the travellers are also excluded because the focus lies on the network perspective. It is dependent on the data and the choice for the parameters, which utility function will give the most accurate approach, therefore the precise function of the utility function will be elaborated in chapter 4 after the data has been collected.

With the utility function, the probability that a certain alternative is chosen can be expressed. In a standard multinomial logit model (MNL), the probabilities that an alternative is chosen are given by (Ben-Akiva & Lerman, 1985):

$$P_{od,m,t} = \frac{e^{\mu V_{od,m,t}}}{\sum_m e^{\mu V_{od,m,t}}} \qquad (2.8)$$

In which:

$P_{od,m,t}$ = The probability that mode m is chosen between origin o and destination d at time t [-]
$V_{od,m,t}$ = The utility function between origin o and destination d for mode m at time t [-]
μ = scale parameter of the logit model [-]

Due to the format of the discrete choice model, the scale parameter μ cannot be distinguished from the parameters β and ASC of the utility function. Therefore the arbitrary assumption is made that $\mu = 1$ (Ben-Akiva & Lerman, 1985).

2.3.3 Logsum method

In (Ben-Akiva & Lerman, 1985) the so-called “Logsum method” was introduced as a measure of accessibility. The Logsum takes the denominator of the logit choice model and corrects this with a logarithm, so that it gives the expected utility from a choice. It can be used to link different choices. The Logsum method gives an estimation of the maximum utility, while taking into account the utilities of all alternatives. When the utilities of the alternatives are close together, the Logsum presents a value above the maximum utility. Furthermore, when the number of alternatives with equal utilities increases, the value of the Logsum increases, showing a benefit for having multiple alternatives. The formula for the Logsum method as introduced in (Ben-Akiva & Lerman, 1985) is:

$$V'_{od,agg,t} = \frac{1}{\mu} \ln \sum_{m} e^{\mu V_{od,m,t}} \qquad (2.9)$$

In which:

$V'_{od,m,t}$ = The systematic component of the maximum utility between origin o and destination d for mode m at time t [-]
$V_{od,m,t}$ = The (systematic component of the) utility function between origin o and destination d for mode m at time t [-]
μ = scale parameter of the logit model [-]

The value of the Logsum will be equal to the minimum utility plus a reduction based on the attractiveness of the alternatives. This entails that the Logsum method will thus be equal or merely a small amount less than the minimum utility.

While in (Ben-Akiva & Lerman, 1985) it was proposed as a measure of accessibility, it has also been used as a measure of consumer surplus in the context of logit choice models in (De Jong et al., 2007). Furthermore, (De Boer, 2014) has used and adapted it as an aggregation method for route travel times in the road network. Due to a number of disadvantages of the Logsum method, (de Boer, 2014) proposes a redefinition of the Logsum method so that he can determine the extent of connectivity of a road network. The disadvantages that are mentioned are:

- In the basic formulation the Logsum has an absolute dependence on the number of alternatives, which is independent of the travel times;
- For lower travel times, The influence of having more alternatives is larger than for larger values. This size-dependence is counterintuitive, as for longer travel times (often on longer routes) a higher network density can be expected with more alternatives.
- The Logsum might become negative when the travel times are too small.

It is noted, that the measure which was proposed by (de Boer, 2014), the utility function consisted solely of travel times due to the route aggregation taking place in the road network. This has ensured that no other parameters had to be used. When taking other modes into account (see Table 2.2), this will cause additional complexities, which will be further explored in the next chapter.

2.4 Summary Reliability, Accessibility & Aggregation Methods

In this chapter an overview was given of the definitions and indicators for reliability and accessibility which could be found in literature and practice. The reliability indicators which were selected were: the Average (μ), the Standard Deviation (σ) and the Variation Coefficient (c_v). For accessibility indicators Hansen’s Potential Value measure and the SVIR Accessibility Indicator were selected.

Furthermore, existing travel time aggregation methods were examined and elaborated. The Logsum method as introduced by (Ben-Akiva & Lerman, 1985) is the most theoretically justified and will be therefore further explored in the next chapter to determine if this method can also be used when different modes are considered for the different alternatives.

3 Aggregation over Multiple Modes

Now that the theory behind the reliability and the accessibility has been discussed and a choice has been made which reliability and accessibility indicators will be used, as well as which aggregation method is most suitable, it can be examined how this this aggregation method can be applied for the aggregation over modes. This is done in section 3.1.

In section 3.2 this aggregated travel time will be used to determine the method with which the reliability of the travel times (paragraph 3.2.1) and the reliability of the accessibility (paragraph 3.2.2) can be determined. This will have consequences for the data collection method, which will be explained in paragraph 3.2.3.

3.1 Aggregation of Travel Times over Multiple Modes

As mentioned in the previous chapter, the proposed adaptation of the Logsum method in the thesis of (de Boer, 2014) provided an adequate method for the aggregation of travel times for a route of an OD-pair in the road network.

In this section, it is examined if the Logsum method can also be used as an aggregation method when alternatives are distributed over different modes. This causes additional complexity as now mode choice also plays an important role. This has consequences for the parameters that are used to determine the utility functions. The values of these parameters will be largely dependent on the network and the used data. The numeric values of said parameters for the actual case study will be elaborated in chapter 4.

If the utility function with mode-specific parameters β_m and ASC_m is implemented into the Logsum method introduced in equation 2.9, this gives:

$$V'_{od,agg,t} = \frac{1}{\mu} \ln \sum_{m} e^{\mu(ASC_m + \beta_m * TT_{od,m,t})} \tag{3.1}$$

Hereby, the "Logsum" is expressed as an aggregated utility over all modes between an origin o and a destination d at a specific time t. However, as depicted in the previous chapter, most reliability and accessibility indicators require a travel time as input to calculate the reliability and accessibility respectively. Therefore, the Logsum method will be rewritten so that an "aggregated travel time" can be found. However, this provides some challenges as to which parameters to use for the β and ASC, when calculating the travel time out of the utility. For now, these parameters will be expressed as β_{LS} and ASC_{LS}. This looks as follows:

$$TT'_{od,agg,t} = \frac{1}{\beta_{LS}} \left(\frac{1}{\mu} \ln \sum_{m} e^{\mu(ASC_m + \beta_m * TT_{od,m,t})} - ASC_{LS} \right) \tag{3.2}$$

Due to the format of the discrete choice model, the scale parameter μ cannot be distinguished from the parameters β and ASC. For convenience the arbitrary assumption is made that $\mu = 1$. This would cause the formula to look like:

$$TT'_{od,agg,t} = \frac{1}{\beta_{LS}} \left(\ln \sum_{m} e^{(ASC^*_m + \beta_m * TT^*_{od,m,t})} - ASC_{LS} \right) \tag{3.3}$$

Although, the exact value of the parameters β_{LS} and ASC_{LS} is unknown yet (and will be determined in chapter 4 as they will be based on the collected data), it is known that they will be related to the parameters β_m and ASC_m of the different modes m respectively.

As mentioned in the previous chapter, the parameter ASC_m expresses the relative preference of mode m compared to another mode; one mode will thus have an $ASC_m = 0$ and will be expressed in solely a (valued) travel time. When (re)calculating the aggregated travel time, the formula will be most theoretically legitimate if the parameters of this mode will be used, as the utility of this mode is already expressed in a (valued) travel time. With $ASC_{LS} = ASC_m = 0$, this parameter will fall out of the equation, making it look like:

$$TT'_{od,agg,t} = \frac{1}{\beta_{LS}}\left(\ln \sum_m e^{(ASC_m + \beta_m * TT_{od,m,t})}\right) \tag{3.4}$$

The Logsum is now expressed solely in a travel time, but is still also influenced by the sensitivity β_m of the mode with $ASC_m = 0$. To obtain a generic absolute travel time, the parameter β_{LS} should then be equal to the β_m of that same mode for consistency reasons. However, there is a risk that the aggregated travel time will become bigger than the minimum travel time (found for the fastest mode) if an arbitrary value for the parameter $\beta_{LS} = \beta_{m|ASC=0}$ is selected. This happens when the parameter $\beta_{LS} = \beta_m$ is used while mode m is not the fastest mode. For instance, if the value of β_{m1} of mode 1 is lower than the value of $\beta_{m3|ASC=0}$ of mode 3 (which has a $ASC_{m3} = 0$) and mode 1 has the fastest travel time, but mode 3 has the highest utility (due to the higher value of β_{m3}), the aggregated travel time will become larger than the aggregated travel time (with $\beta_{LS} = \beta_{m3}$).

This is against the principles of the Logsum method, as the Logsum method will always give a value equal or smaller than the minimum input value. If the value of parameter β_{LS} is equal to the β_m with the lowest value ($\beta_m = \beta_{m|min}$), this would not occur. The value of $\beta_{LS} = \beta_m$ should therefore be equal to the highest absolute value of β_m.

The numeric values for the parameters should thus be selected so, that the mode with $ASC_m = 0$ has the highest (absolute) value for β_m.

3.2 Reliability

Now that the Logsum method has been used to calculate an aggregated travel time over multiple modes, it is possible to compare this aggregated travel time with the travel times of the individual modes. The travel times and aggregated travel time are compared for the reliability, accessibility and the reliability of the accessibility.

3.2.1 Reliability of Travel Times

Like the travel times that are used as input, the aggregated travel time is determined for a certain origin-destination pair at a certain time point t. Because the travel time and aggregated travel time are determined for a specific time point, it can vary greatly over time. With the existing reliability indicators presented in the previous chapter (paragraph 2.1.2), the reliability of these (aggregated) travel times can be presented. The following reliability indicators were selected:

- Average (μ)
- Standard Deviation (σ)
- Variation Coefficient (c_v)

To be able to calculate these reliability indicators, travel times for multiple time points should be collected & calculated. Two situations can be distinguished:

- Reliability within a Day
- Reliability over Days

For *Reliability within a Day* the travel times are collected for different time points of the same day. Ideally, these time points would be spread out over the day and would encompass different time periods in the day, such as morning peak, afternoon, evening peak, evening and optionally night, so that a large diversity of travel times can be obtained. Some periods are more sensitive for travel time delays than others: generally, it is expected that the travel times in rush hour peaks are higher for individual modes of transport (i.e. the road network), where travel time delays are often a result of incidents and/or congestion (due to the number of other travellers on the road). The other networks (public transport and bicycle) are less sensitive for these disruptions, because the public transport network is bound by the time tables, and the bicycle networks delays do not occur.

Reliability over Days is determined by calculating the reliability for a specific time point (for instance 9:00 am every morning) over a number of days. The Reliability over Days could be determined over weekdays (Mondays to Sundays), over workdays (Mondays to Fridays) or even over specific days (every Monday for a certain amount of weeks/months).

Because of the additional alternatives that are taken into account, the reliability of the aggregated travel time over multiple modes is expected to be higher than those of the separate modes. This will be explored with a case study in the next chapter (chapter 4).

3.2.2 Accessibility & Reliability of the Accessibility

Besides the travel time reliability, the collected travel times and the aggregated travel time can also be used to determine the accessibility per mode and the accessibility over multiple modalities respectively using the indicators given in paragraph 2.2.2. Like the travel times before, these accessibility indicators are determined at a certain time point t. Because of the expected variation in the collected travel times (particularly the car travel times during peak hours), the accessibility is also expected to vary over time.

The same reliability indicators (elaborated in paragraph 2.1.2 and mentioned in the previous paragraph) can be used to determine the reliability of the network at a location/zonal level: the reliability of the accessibility. As was the case for the travel time reliability, the reliability of the accessibility can be determined for two situations:

- Reliability within a Day
- Reliability over Days

For both situations, the same data can be used as for the travel time reliability.

3.2.3 Data Collection Method

To determine the reliability within a day and the reliability over days for multiple modalities for both the travel times as well as the accessibility, data needs to be collected with the following requirements:

- The travel times need to be collected for multiple time points t during a day;
- The travel times need to be collected at a specific time point t during multiple days;
- These travel times need to be collected for multiple modes (car, public transport & bike).

Traditional data sources that are used to determine the travel time reliability consist of data collection loops, OViN data and transport models. However, data collection loops are only available for the road network and provide only link data, OViN data consists of only partial subjective data (depending on which trip was made) and transport models use average travel times (for the car network) or timetable data (for the public transport network). Furthermore, only models can simultaneously give information on the road network, public transport network and the bicycle network.

Google is considered as a data source to see if the data can be collected. Google Maps has a collection with historical travel times for multiple modes and multiple time points. At the start of the research it was planned to use these historical travel times, but unfortunately the quality and level of detail of these data sources were not sufficient. Fortunately, an alternative presented itself in an alternative provided by Google itself: the Google Maps API's. Several are available, but for this research the Distance Matrix API was used. The travel times could be collected for multiple time points (both during one day and over days) and were available for multiple modes. During the data collection phase, described in the next chapter, this method will be further elaborated (paragraph 4.1.2).

3.3 Summary Aggregation over Multiple Modes

In this chapter it has been explored if the Logsum method as introduced by (Ben-Akiva & Lerman, 1985) could also be used for aggregation of travel times if the alternatives consisted of different modes. It has been found that the Logsum method could be used as an method to find an aggregated travel time provided that the numeric values for the parameters β_{LS} and ASC_{LS} (which are used to calculate the "aggregated travel time" out of the aggregated utility) are equal to that of the mode which has $ASC_m = 0$ and the highest (numeric) value for β_m (compared to the β_m's of the other modes).

Furthermore, it has been decided that with help of the indicators introduced in the previous chapter, the travel time reliability and the reliability of the accessibility can be determined. Two situations were distinguished:

- Reliability within a Day
- Reliability over Days

In order to determine the reliability and the reliability of the accessibility, the travel times should be collected for multiple time points. These time points should be distributed over multiple moments within a day and also over multiple days. It has been deducted that collected data is better suited for this purpose than using data constructed by models, as models are already using averages which would not give the desired variability in the travel time distribution.

4 Case Study Amsterdam

To test the practical application of the adapted theory as described in the previous chapter, a case study is conducted for the city of Amsterdam.

In section 4.1, the setup of the case study will be explained, which starts with the choice for the locations. The classification of locations and of the OD-relations will be addressed in paragraph 4.1.1, the elaboration on the data collection method which was used is given in paragraph 4.1.2. Choices for the collected data are given and elaborated in paragraph 4.1.3 and comments on the quality of the collected data are given in paragraph 4.1.4.

In section 4.2, the aggregation over multiple modes is done with the aggregation method as described in chapter 3. The travel time reliability will be determined in section 4.2.2 (where a distinction is made between travel time reliability within a day, which is addressed in paragraph 4.3.1, and travel time reliability over days, addressed in paragraph 4.3.2). In section 1.1.1, the accessibility and the reliability of the accessibility will be calculated. The distinction between reliability within a day (paragraph 4.3.3) and reliability over days (paragraph 4.3.4) is also made here.

4.1 Setup Case Study Amsterdam

The case study will focus on the city of Amsterdam in the Netherlands. The locations are chosen so that they correspond with the geographical midpoints of the city districts of the municipality of Amsterdam. The locations are shown in Figure 4.1, where the colours represent the different city districts as indicated by the legend on the right side, and the point of the black bulbs indicate the locations that are used for the origin and destinations.

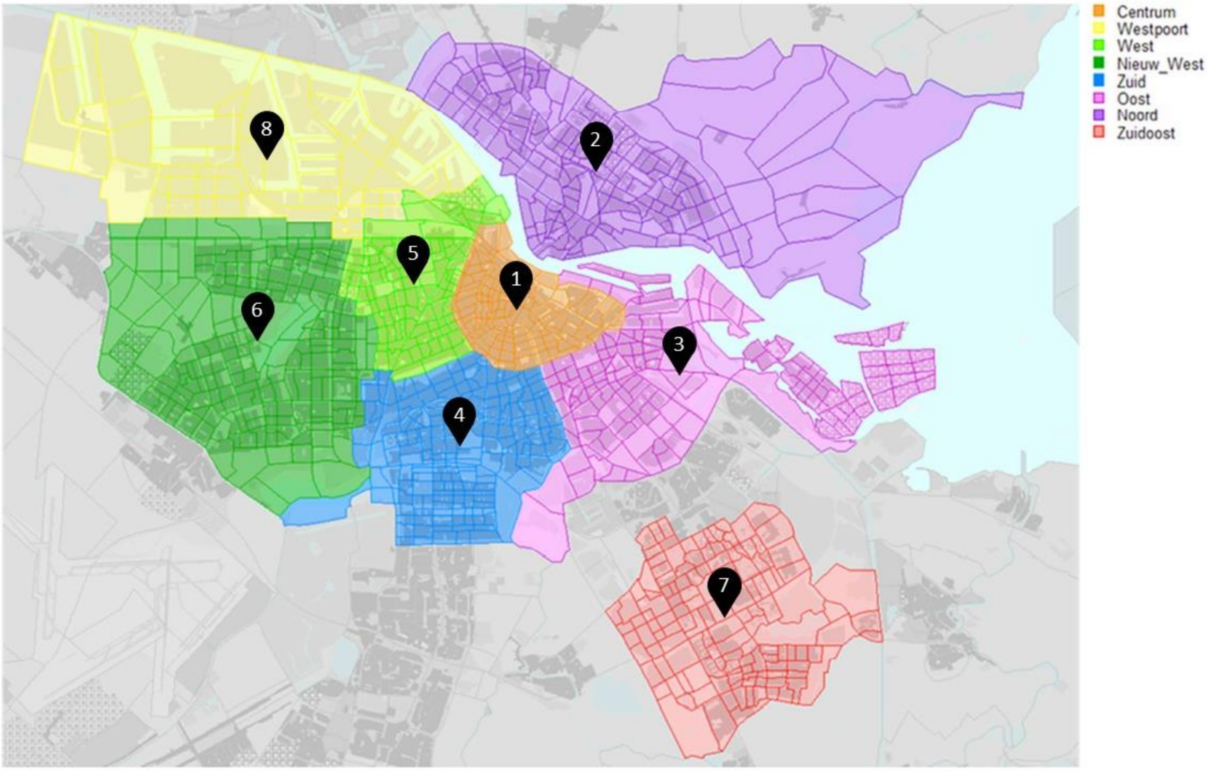


Figure 4.1 City districts in Amsterdam (Pieters, van den Elshout, & Herder, 2014)

In Table 4.1 the coordinates of these locations is given. For the calculation of the accessibility, the number of inhabitants/jobs is needed. For this, the inhabitants/jobs of the city district in which the origin/destination node lies is used. These are also shown in Table 4.1. The data have been found on the website and in the publications of the Research, Information and Statistics department of the municipality of Amsterdam (Onderzoek, Informatie en Statistiek, 2016).

Table 4.1 Data of city districts in Amsterdam (*data from (Onderzoek, Informatie en Statistiek, 2016))

origin/ destination*	origin/destination Name*	Latitude-coordinate	Longitude-Coordinate	Inhabitants*	Employed Persons*
1	'Centrum'	52,37076	4,89591	86.499	99361
2	'Noord'	52,40027	4,92376	92.917	30639
3	'Oost'	52,35632	4,95520	132.421	60412
4	'Zuid'	52,34195	4,87745	143.258	102907
5	'West'	52,37548	4,86197	143.964	47736
6	'Nieuw_West'	52,36304	4,80975	149.397	72042
7	'Zuidoost'	52,30689	4,96739	86.057	75427
8	'Westpoort'	52,40134	4,81165	200	21420

As seen in Table 4.1, location 8 ('Westpoort') has very few inhabitants, since it is mostly an industrial area. The number of employed persons is higher in this area. This is something to keep in mind when calculating the accessibility using the Potential Value (the SVIR accessibility indicator does not use the number of inhabitants in the formula). It is expected that the potential value of location '08_Westpoort' does not give a distinctive value or a value that is very small compared to the other locations.

4.1.1 Classification of location and OD-relations

Once the data has been collected and the reliability has been determined (of both the travel times and the accessibility), the results will be used to assess the locations and the connections between the locations. However, when doing so, the characteristics of the locations and the OD-relations compared to the other locations and OD-relations will play an important role. In this paragraph a classification of the locations and OD-relations is proposed, so that the assessment will be made for comparable OD-pairs.

First, the locations are classified by being located either in a relative central location or on the outskirts of the city. This is shown in Table 4.2. Notably, only two locations are located on the inside of the city.

Table 4.2 Classification of the selected locations

Locations in a central location	Locations on the edges of the city
01_Centrum	02_Noord
05_West	03_Oost
	04_Zuid
	06_Nieuw-West
	07_Zuidoost
	08_Westpoort

The classification of the OD-relations are based on the (crow fly) distance between an origin and destination, which are given in Table 4.3. If the origin and the destination location are the same, the distance is equal to zero (no internal trips will be taken into account).

Table 4.3 Distances between origins & destinations (in km)

	01_ Centrum	02_ Noord	03_ Oost	04_ Zuid	05_ West	06_ Nieuw -West	07_ Zuid oost	08_ West poort
01_Centrum	0	3,8	4,3	3,4	2,4	5,9	8,6	6,7
02_Noord	3,8	0	5,3	7,2	5	8,8	10,8	7,6
03_Oost	4,3	5,3	0	5,5	6,7	9,9	5,5	11
04_Zuid	3,4	7,2	5,5	0	3,9	5,2	7,3	8
05_West	2,4	5	6,7	3,9	0	3,8	10,5	4,5
06_Nieuw-West	5,9	8,8	9,9	5,2	3,8	0	10,5	4,5
07_Zuidoost	8,6	10,8	5,5	7,3	10,5	10,5	0	14,9
08_Westpoort	6,7	7,6	11	8	4,5	4,5	14,9	0

It is noted that all distances are under the 15 km. Based on these distances, three distance classes have been distinguished:

- Short distances (< 5 km);
- Medium distances (5 – 10 km);
- Long distances (> 10 km).

When applied on the OD-relations, this results in Table 4.4.

Table 4.4 Classification of OD-relations by distances

	01_ Centrum	02_ Noord	03_ Oost	04_ Zuid	05_ West	06_ Nieuw -West	07_ Zuid oost	08_ West poort
01_Centrum	0	< 5	< 5	< 5	< 5	5 - 10	5 - 10	5 - 10
02_Noord	< 5	0	5 - 10	5 - 10	5 - 10	5 - 10	> 10	5 - 10
03_Oost	< 5	5 - 10	0	5 - 10	5 - 10	5 - 10	5 - 10	> 10
04_Zuid	< 5	5 - 10	5 - 10	0	< 5	5 - 10	5 - 10	5 - 10
05_West	< 5	5 - 10	5 - 10	< 5	0	< 5	> 10	< 5
06_Nieuw-West	5 - 10	5 - 10	5 - 10	5 - 10	< 5	0	> 10	< 5
07_Zuidoost	5 - 10	> 10	5 - 10	5 - 10	> 10	> 10	0	> 10
08_Westpoort	5 - 10	5 - 10	> 10	5 - 10	< 5	< 5	> 10	0

4.1.2 Google Maps Distance Matrix API

As mentioned in the previous chapter (paragraph 3.2.3), initially the data for the case study would consist of the historical travel times as collected by Google using the GPS-locations of their users' phones. Unfortunately, this data turned out not to be available, so a new alternative was needed to still obtain a data set with travel times of various times (and days) as well as the multiple modes. It is chosen to collect the (estimated) travel times using the Google Maps Distance Matrix API instead. The details of this method will be explained below.

The Google Maps Distance Matrix API is a service provided by Google Maps that provides travel distance and time for a matrix of origins and destinations (Google Developers, 2017). API is the abbreviation for Application Programming Interface. It is a set of definitions that allow a computer program to communicate with another program or component.

The Google Maps Distance Matrix API is a web service provided by Google which can be used to retrieve the duration and distance between start and end point(s) based on a recommended route. (Google Developers, 2017). The Google Maps API estimates travel times and distance for multiple modes including the (expected) delays.

The Google Maps Distance Matrix API returns the travel time and distance between (a set of) origin(s) and destination(s). The API automatically selects the recommended route. Google Maps APIs provide a number of options to specify (if desired), which can be included in the web-address and influence the output. The ones that are relevant for this research are listed below (Google Developers, 2017):

- **Mode:** to specify the mode of transport to use when calculating the distance and travel times. The API defaults to the mode ‘driving’. Other supported modes are: ‘walking’, ‘bicycling’ and ‘transit’.
- **Arrival/Departure Time:** to specify the departure or arrival time of the request. The desired time of departure or arrival should be specified by an integer, in seconds since January 1,1970 UTC. If not specified the departure time defaults to ‘now’. Logically, either the departure time or the arrival time can be specified (so not both). Furthermore, a few limitations are in place:
    - Departure time in the past can only be used for ‘transit’; for the modes ‘driving’, ‘bicycling’ and ‘walking’ the departure time needs to be set to ‘now’ or in the future.
    - Arrival time in the future can only be set for the modes ‘driving’, ‘bicycling’ and ‘walking’; for ‘transit’ the arrival time needs to be set in the past or to ‘now’.
    - It is possible to receive a route and trip duration that takes traffic conditions into account. However, this is only possible for the mode ‘driving’ and if the departure time is set to the current time or sometime in the future.
- **Traffic Model:** to specify the assumptions that are used when calculating the time spent in traffic (only applicable for requests with travel mode is ‘driving’ and a departure time set to ‘now’ or in the future). This setting defaults to ‘best guess’, which indicates that the returned ‘duration in traffic’ is the best estimate of travel time given what is known about both historical traffic conditions and the current “live traffic” (at the time the request is made). Other possible values are ‘pessimistic’ (the returned ‘duration in traffic’ is longer than actual travel time on most days) and ‘optimistic’ (the returned ‘duration in traffic’ is shorter than actual travel time on most days).

4.1.3 Collected Data

As mentioned in the previous paragraph, the data was collected using the Google Maps API. This was done for three modes: ‘driving’, ‘transit’ and ‘bicycling’. Initially, ‘walking’ was also included, but since the distances between the locations were quite large (for walking purposes at least), it was deducted that walking would not be an attractive alternative so was therefore excluded.

During the collection period the departure time was set to the default setting ‘now’, meaning that the data was collected *real time*, so the most accurate travel time information on delays could be obtained. It was decided not to collect real time travel times for the mode ‘bicycling’ when a quick study revealed that these times were mostly constant over time with a minimum number of very small disturbances. Therefore, including these in the data collection intervals, would only use an unnecessary amount of requests with no additional benefit. Instead, the bicycle travel times were collected at a specific time point and then used for the other time points as well. The data for the modes ‘driving’ and ‘transit’ were collected using real time travel information, so that delays were also included.

MATLAB (MathWorks, 2016) was used to automatically request and collect the car and public transport travel times with a certain time interval during the day. The time interval during a day are given in Table 4.5: during the peak hours (7:00 – 10:00 & 16:00 – 19:00) every 5 minutes requests were made, while during the rest of the day this interval consisted of 30 minutes.

The decision was made not to collect any data during night hours (23:00 – 7:00), because of the limited amount of requests that could be done to the Google Maps API during one day and because these data would likely not be used as the focus would lie on the peak hours and the non-peak hours during daytime. A MATLAB-script was written so the collection would take place continuously for all days during the week (both workdays and weekend days).

Table 4.5 Data collection information for driving & public transit

Time Period	Time	Interval between 2 data collection moments
Morning Peak	7:00 – 10:00	5 minutes
Evening Peak	16:00 – 19:00	5 minutes
Rest Day	10:00 – 16:00 19:00 – 23:00	30 minutes
Night	23:00 – 07:00	No data collected (8 hours interval)

Unfortunately, the data collection method proved to be less than ideal. The MATLAB-script kept repeatedly terminating due to an ‘Internal Service Error’ of the Google Maps API. As a result, the number of days for which travel times were collected, was far lower than previously aimed for. The days for which the travel times were ultimately included in the reliability calculations are given in Table 4.6. The dates marked with a star(*) are incomplete with regard to the time points for which travel times were collected (meaning that not for all of the time points per day travel times were collected), but are still included because either the first part of the day was complete and adjacent to time points of the previous day before the MATLAB-script was terminated or the MATLAB-script was started up again and the later part of the day was complete and adjacent to time points of the next day.

Table 4.6 Dates for which Travel Times were selected

March / April	May / June
Friday March 24th 2017	Wednesday May 31st 2017*
Saturday March 25th 2017	
Sunday March 26th 2017	Thursday June 1st 2017
Monday March 27th 2017	Friday June 2nd 2017*
Tuesday March 28th 2017*	Thursday June 8th 2017*
Friday March 31st 2017*	Friday June 9th 2017
	Saturday June 10th 2017
Saturday April 1st 2017	Sunday June 11th 2017*
Sunday April 2nd 2017	Wednesday June 14th 2017*
Monday April 3rd 2017	Thursday June 15th 2017
Tuesday April 4th 2017	Friday June 16th 2017*
Wednesday April 5th 2017	Thursday June 22nd 2017*
Thursday April 6th 2017	Friday June 23rd 2017
Friday April 7th 2017*	Saturday June 24th 2017
Friday April 21st 2017	Sunday June 25th 2017
Saturday April 22nd 2017	Monday June 26th 2017
Sunday April 23rd 2017	Tuesday June 27th 2017
	Wednesday June 28th 2017*

4.1.4 Quality of Collected Data

In Appendix A the travel time distributions for origin location '01_Centrum' are given. It is noted that the travel times for public transit are much higher than those for the car and bike. This raises the question what the quality is of the public transit data collected with the Google Maps API.

To verify the quality of public transit travel times collected with the Google Maps Distance Matrix API, the travel times of the Google Maps API are compared with the travel times that would be given using the normal Google Maps website (Google, 2016) and with the 9292 website (REISinformatiegroep B.V., 2017). The results are given in Appendix B.

In summary, it can be said that:

- As expected, Google Maps and the Google Maps API return the same (expected) travel times for public transport.
- When asking for the travel times at a time point in the past or in the future, all three data sources return the travel times based on the time table. When retrieving the travel times at the current time, the current delays are also taken into account. So, for all three data sources the (expected) travel time is based on the current traffic situation (if the current time is selected) or on the time table (if a time in the future or the past is selected).
- No historic data is stored for the public transport (in either of the data sources).
- For most OD-relations, Google Maps and 9292 return comparable same travel times, with no or small deviations (only 1 or 2 minutes).

- For some OD-relations the differences between the retrieved travel times are larger: 9292 found a significantly faster trip than Google Maps did. This was mostly due to selecting a later departure time (which 9292 varies, but Google does not), different itineraries or different strategies used by the sites: 9292 minimizes the total travel time, while Google minimizes the number of transfers and minimizes the travel time from the departure time which is supplied.
- One location could not be found in 9292 (location ’07_zuidoost’). For Google Maps & the Google Maps API this could be found, because for these sources it is also possible to search for GPS-coordinates. If 9292 would be used, a location close by needs to be looked up and selected. This was not done in this research because of time constraints.
- The selected locations were located in the middle of the city districts: this caused some additional access and egress times for public transport, as these locations were not always located nearby a central point (especially in zone ‘01_Centrum). However, not all addresses are located near a public transport stop in reality, so this would give a reasonable representation of reality.
- All access and egress to and from public transport is done by walking for either of the data sources. Bicycling is not considered as an access or egress mode, though is likely often considered in reality. To be fair, for the modes car and bicycling the access and egress times to or from the car/bike would also be done by walking, although these times are not included by the data source(s).

4.2 Data Processing

After the travel times have been collected with the Google Maps Distance Matrix API, the travel times need to be processed so that the aggregated travel time can be calculated, before the travel time reliability and the reliability of the accessibility can be calculated.

4.2.1 Aggregation of Travel Times over Multiple Modalities

After the travel times were collected, the aggregated travel time was determined using the method as described in the previous chapter (section 3.1). Now that the data is known, first the parameters for in the utility functions need to be established. As shown in Table 2.2 in paragraph 2.3.2, there are four options for the utility function:

- Utility function with fixed β and no ASC;
- Utility function with fixed β and mode-dependent ASC (ASC_m);
- Utility function with mode-dependent β (β_m) and no ASC);
- Utility function with mode-dependent β (β_m) and mode-dependent ASC (ASC_m).

These options have been explored and for each of the options, the numeric values for the parameters have been estimated so that a reasonable Modal Split was found. This analysis can be found in Appendix C.

Concluding, it can be said that the values for the parameters are dependent on the data and are of relatively large influence on the modal split and thus on the aggregated travel time. The values for the parameters were estimated so that a plausible modal split was found, this was based solely on the researchers expert judgment.

For the remainder of this research, the utility function with mode-dependent β (β_m) and mode-dependent ASC (ASC_m) was selected, because this function gives the most appropriate and realistic modal split in the researchers opinion. The utility function looks thus as follows with the values for the parameters are given in Table 4.7:

$$V_{od,m,t} = ASC_m + \beta_m * TT_{od,m,t} \tag{4.1}$$

Table 4.7 Values for parameters β_m and ASC_m

Parameter	Value [-]	Parameter	Value [1/min]
$\boldsymbol{ASC_{car}}$	-1	$\boldsymbol{\beta_{car}}$	-0,3
$\boldsymbol{ASC_{pt}}$	-3	$\boldsymbol{\beta_{pt}}$	-0,25
$\boldsymbol{ASC_{bike}}$	0	$\boldsymbol{\beta_{bike}}$	-0,4

4.2.2 Travel Time Reliability

To determine the travel time reliability of the network, the Average (μ), the Standard Deviation (σ) and the Variation Coefficient (c_v) have been calculated. A distinction is made between the travel time reliability within a day and the travel time reliability over days.

In the first case (the travel time reliability within a day) the averages, standard deviations and variation coefficients are calculated for the travel times collected during one day at different time points. The first Monday of the collected data was selected for this: Monday March 27th 2017.

For the travel time reliability over days the averages, standard deviations and variation coefficients are calculated for the travel times collected during a certain time over all days in the collected data. This was done for the data collected at 9:00 am. This time was chosen, because it was during rush hours and had the most delays during the morning peak hours according to the travel time distributions in Appendix A.

4.2.3 Reliability of the Accessibility

The accessibility of the locations in the mid-points of the Amsterdam city districts are calculated using the formulas for Hansen's Potential Value and the SVIR Accessibility Indicator as described in paragraph 2.2.2.

Before the accessibility indicators could be calculated, the values for the variables need to be determined. For the Potential Value, the numeric values for the variables M_j and $f(C_{ij}) = 1/C_{ij}^b$ need to be determined. For the mass M_d the inhabitants for destination location d as given in Table 4.1 are used. For the cost function C_{ij} the utility between origin o and destination d will be selected ($C_{ij} = U_{od,m,t}$) and $b = 2$, thus making $f(C_{ij}) = 1/U_{od,m,t}^2$, so that the total formula becomes:

$$PV_o = \sum_d M_d * \frac{1}{U_{od,m,t}^2} \tag{4.2}$$

For the SVIR Accessibility Indicator the variables P_{ij} (the number of movements between origin zone i to destination zone j), TT_{ij} (the travel time between origin zone i to destination zone j) and d_{ij} (the distance between origin zone i to destination zone j) still need to determined.

For the number of movements, the traffic model VENOM (Vervoerregio Amsterdam, 2016) is considered. Since VENOM does not have information on the number of movements from one exact location to another, the number of movements from the city districts are used. In VENOM, matrices are stored with information on the number of movements per mode. The matrices for car, bicycling and public transport will be used. However, when looking up these matrices, the matrices for bicycling and public transport were found to be empty, thus making it impossible to use these data. An explanation for this unwanted scenario has not been found. As a solution, it has been decided to use the car movements also for the other modes, though it is noted this might give a distorted result. The number of movements that are used, are given in .

Table 4.8 Number of Car Movements between Origin & Destination as found in VENOM (Vervoerregio Amsterdam, 2016)

	01_ Centrum	02_ Noord	03_ Oost	04_ Zuid	05_ West	06_ Nieuw-West	07_ Zuid oost	08_ West poort
01_Centrum	8921	4568	7553	5659	5991	3455	2563	1307
02_Noord	1993	32366	5361	2469	3735	2492	1362	1833
03_Oost	7059	5919	26331	10153	4652	3131	6924	2569
04_Zuid	7347	1461	8115	30130	6970	8493	4322	2317
05_West	4708	4436	5291	8910	15531	12731	2164	4828
06_Nieuw-West	2692	3056	3680	8527	14613	30122	1862	7833
07_Zuidoost	2838	1907	6999	4864	2118	1567	25343	912
08_Westpoort	717	2054	2136	2546	4896	7087	769	2322

For the travel time between origin i and destination j, the collected travel times between origin location o and destination location d for mode m at time t was used ($TT_{ij} = TT_{od,m,t}$). For the distance between origin i an destination j, the distances as found in Table 4.3 in paragraph 4.1.1 between origin location o and destination location d were used ($d_{ij} = d_{od}$). The total formula then becomes:

$$AI_d = 1/\frac{\sum_{o=1}^{O} P_{od} * TT_{od,m,t}}{\sum_{o=1}^{O} P_{od} * d_{od}} \tag{4.3}$$

The accessibility indicators were calculated for each specific time point t in time. To be able to comment on the reliability of the accessibility over the different time points, the averages and standard deviations along with the variation coefficients are determined.

As was the case for the travel times for the different OD-relations, the reliability of the accessibility is determined within a day and over days. The reliability within a day is decided for the first Monday of the collected data: Monday March 27th. The reliability over days is decided for 9:00 am of all days in the collected data.

4.3 Results

Now that the travel times has been processed, the travel time reliability within a day and over days and the reliability of the accessibility within a day and over days can be determined. The results are given in this section.

4.3.1 Travel Time Reliability within a Day

The average travel times within a day are determined alongside the standard deviations for one day: Monday March 27th. The OD-relations are divided into their distance classes as described in paragraph 4.1.1, so that the OD-relations can be compared with equivalent OD-relations of the same distance. The averages and standard deviations are visualized in Figure 4.2 for the short distances (<5 km), in Figure 4.3 for the medium distances (5-10 km) and in Figure 4.4 for the long distances (>10 km).

Short Distances

The average travel times and standard deviations within a day for short distances (<5km) are shown in Figure 4.2.

At first glance, one immediately notices that the averages for public transit are higher than those of the other modes, indicating that public transit is thus often the least attractive alternative between two locations, though this was to be expected due to the high travel times. Furthermore, the standard deviations of the public transit travel times are also larger than those of the other modes, making this mode even less attractive.

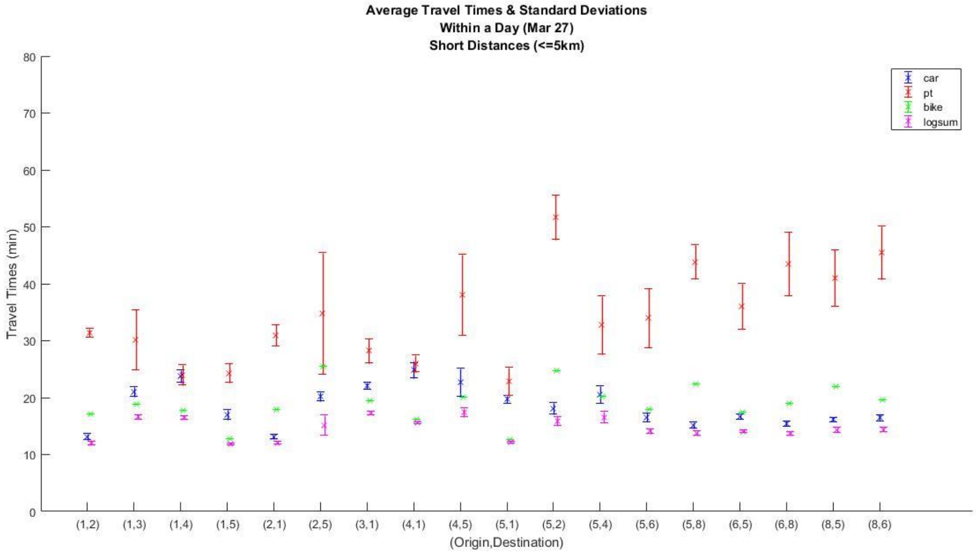


Figure 4.2 Average travel times with standard deviations for OD-relations short distances (<5 km) within a day

The standard deviations of bike are 0, due to the fact that the travel times are collected for one time point only and are thus constant over time. Generally, the Logsum shows the lowest averages and small standard deviations, indicating that the multimodal network is indeed more reliable than the separate modes. Note that, due to the method that was used, the aggregated travel times over multiple modes are always lower than those of the separate modes. If then the average and the standard deviation of these aggregated travel times are determined, the results will be lower than those of the separate modes by default.

Due to the short distances, the bike travel times rival the travel times for the car. This is reflected in the resulting aggregated travel times. The relations ‘01_Centrum’-‘04_Zuid’, ‘04_Zuid’-‘01_Centrum’, and ‘05_West’-‘01_Centrum’ have PT and car travel times that are closely related, due to their location in the network (all three locations are close to each other (at least compared to the other locations). The bike travel times are even lower than that, thus making the bike the most influential mode for the aggregated travel time.

The relations ‘02_Noord’-‘05_West’ and ‘04_Zuid’-‘05_West’ have large standard deviations for PT travel times. Furthermore, the relation ‘05_West’-‘02_Noord’ has a high average for PT travel times. Improving these connections would be most beneficial.

In Table 4.9 the variation coefficients for these relations are given. As said before the variation coefficient is a standardized measure and is defined as the ratio between the standard deviation σ and the mean μ. The relations '04_Zuid'-'05_West' and '05_West'-'04_Zuid' have relatively high variation coefficients for car and PT, resulting in relatively high variation coefficient for the Logsum as well. Furthermore, the relations '02_Noord'-'05_West' and '05_West'-'02_Noord' also have high variation coefficients for the Logsum. Overall, the variation coefficients for PT are relatively high, thus indicating that the ratio between standard deviation and average is quite large, which makes this an unreliable (and thus unattractive) mode.

Table 4.9 Variation Coefficients for OD-relations short distances (<5 km) within a day

	Car	PT	Bike	Logsum
'01_Centrum'-'02_Noord'	9%	5%	0%	6%
'01_Centrum'-'03_Oost'	8%	35%	0%	4%
'01_Centrum'-'04_Zuid'	9%	15%	0%	4%
'01_Centrum'-'05_West'	10%	14%	0%	3%
'02_Noord'-'01_Centrum'	6%	12%	0%	4%
'02_Noord'-'05_West'	7%	61%	0%	23%
'03_Oost'-'01_Centrum'	5%	15%	0%	3%
'04_Zuid'-'01_Centrum'	11%	11%	0%	2%
'04_Zuid'-'05_West'	22%	37%	0%	9%
'05_West'-'01_Centrum'	7%	22%	0%	2%
'05_West'-'02_Noord'	11%	15%	0%	10%
'05_West'-'04_Zuid'	15%	31%	0%	11%
'05_West'-'06_Nieuw-West’	9%	31%	0%	6%
'05_West'-'08_Westpoort'	7%	14%	0%	6%
'06_Nieuw-West’-'05_West'	5%	22%	0%	4%
'06_Nieuw-West’-'08_Westpoort'	6%	26%	0%	5%
'08_Westpoort'-'05_West'	5%	24%	0%	5%
'08_Westpoort'-'06_Nieuw-West’	7%	20%	0%	5%

Medium Distances

The average travel times and standard deviations within a day for medium distances (5-10km) are shown in Figure 4.3. Again, the mode public transit show the highest averages, along with the highest standard deviations, making this the least attractive alternative. The aggregated travel time (‘Logsum’) shows the lowest averages, as well as low standard deviations. Though this was attributed to the method that was used.

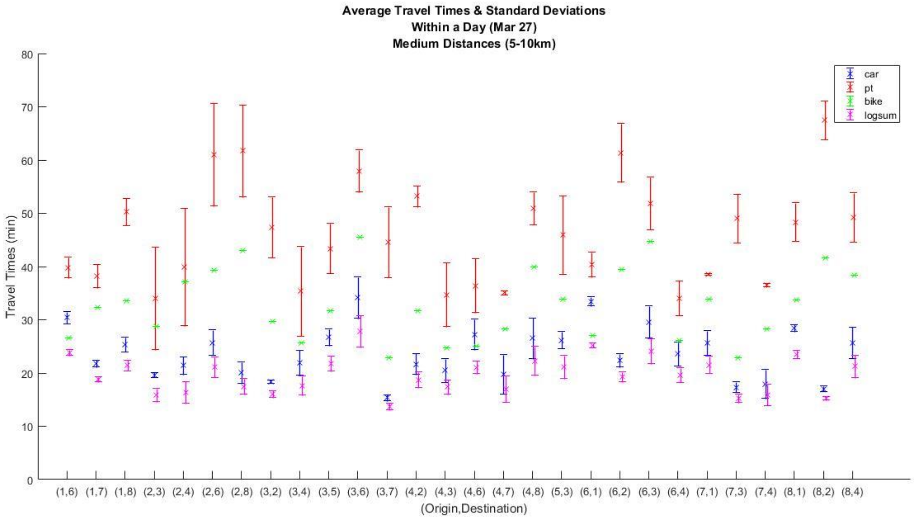


Figure 4.3 Average travel times with standard deviations for OD-relations medium distances (5-10 km) within a day

Generally, the car travel times have the lowest travel times (as indicated by the averages), thus resulting in the aggregated travel times being largely influenced by the car. The exception to this is the relation ‘01_Centrum’-‘06_Nieuw-West’, where the bike shows the lowest travel times (due to being closely related) and has thus the most influence on the aggregated travel time.

Table 4.10 shows the variation coefficients for OD-relations with medium distances. Compared to the short distances, these OD-relations show higher variation coefficients, which could be due to the larger distances (and thus automatically higher average travel times).

Table 4.10 Variation Coefficients for OD-relations medium distances (5-10 km) within a day

	Car	PT	Bike	Logsum
'01_Centrum'-'06_Nieuw-West’	7%	10%	0%	5%
'01_Centrum'-'07_Zuidoost'	6%	12%	0%	5%
'01_Centrum'-'08_Westpoort'	11%	10%	0%	9%
'02_Noord'-'03_Oost'	5%	57%	0%	16%
'02_Noord'-'04_Zuid'	16%	55%	0%	25%
'02_Noord'-'06_Nieuw-West’	18%	32%	0%	18%
'02_Noord'-'08_Westpoort'	20%	28%	0%	17%
'03_Oost'-'02_Noord'	3%	24%	0%	8%
'03_Oost'-'04_Zuid'	22%	48%	0%	20%
'03_Oost'-'05_West'	12%	22%	0%	13%
'03_Oost'-'06_Nieuw-West’	23%	14%	0%	21%
'03_Oost'-'07_Zuidoost'	8%	30%	0%	9%
'04_Zuid'-'02_Noord'	18%	7%	0%	16%
'04_Zuid'-'03_Oost'	22%	35%	0%	16%
'04_Zuid'-'06_Nieuw-West’	21%	28%	0%	11%
'04_Zuid'-'07_Zuidoost'	37%	2%	0%	29%

	Car	PT	Bike	Logsum
'04_Zuid'-'08_Westpoort'	28%	12%	0%	24%
'05_West'-'03_Oost'	12%	32%	0%	20%
'06_Nieuw-West'-'01_Centrum'	5%	11%	0%	3%
'06_Nieuw-West'-'02_Noord'	11%	18%	0%	10%
'06_Nieuw-West'-'03_Oost'	20%	19%	0%	20%
'06_Nieuw-West'-'04_Zuid'	19%	19%	0%	14%
'07_Zuidoost'-'01_Centrum'	18%	1%	0%	15%
'07_Zuidoost'-'03_Oost'	11%	19%	0%	10%
'07_Zuidoost'-'04_Zuid'	31%	2%	0%	25%
'08_Westpoort'-'01_Centrum'	5%	15%	0%	6%
'08_Westpoort'-'02_Noord'	6%	11%	0%	5%
'08_Westpoort'-'04_Zuid'	23%	19%	0%	20%

Long Distances

The average travel times and standard deviations within a day for long distances (>10km) are shown in Figure 4.4.

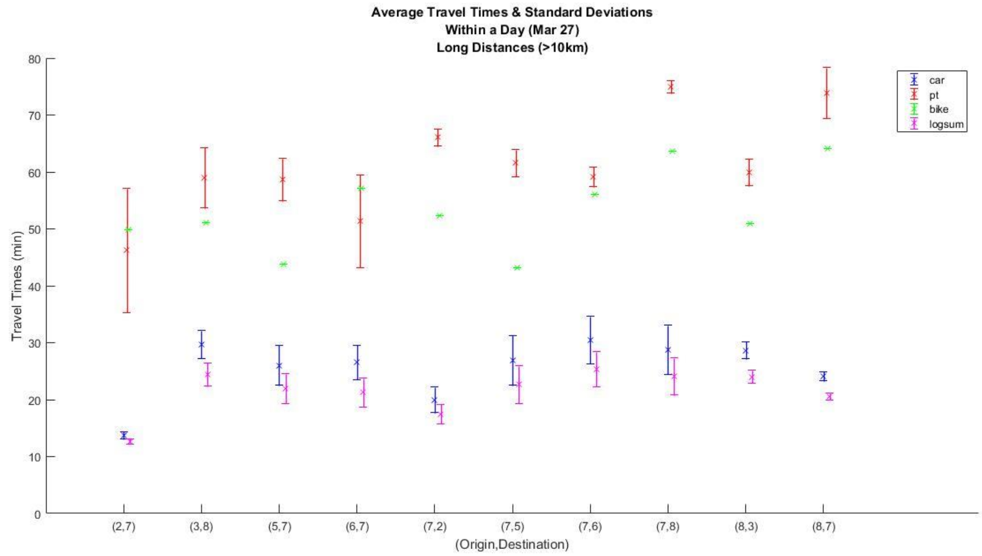


Figure 4.4 Average travel times with standard deviations for OD-relations long distances (>10 km) within a day

Due to the high travel times, public transport is seen as a very unattractive mode. Even though the distances are long, and the bike travel times will therefore be unattractively high, the public transport travel times are still higher for 8 out of the 10 connections. The car travel times are the most attractive according to the averages. Depending on the OD-relation the standard deviations are less unambiguous for this mode.

The variation coefficients for the OD-relations with large distances (>10km) are given in Table 4.11. The OD-relation from location '07_Zuidoost' have a lower variation coefficient for public transport, indicating that although this location has generally high average travel times for public transport, the mode is fairly reliable as the standard deviations are low.

Table 4.11 Variation Coefficients for OD-relations long distances (>10 km) within a day

	Car	PT	Bike	Logsum
'02_Noord'-'07_Zuidoost'	9%	47%	0%	8%
'03_Oost'-'08_Westpoort'	16%	18%	0%	17%
'05_West'-'07_Zuidoost'	27%	13%	0%	24%
'06_Nieuw-West'-'07_Zuidoost'	23%	32%	0%	24%
'07_Zuidoost'-'02_Noord'	22%	5%	0%	19%
'07_Zuidoost'-'05_West'	33%	8%	0%	29%
'07_Zuidoost'-'06_Nieuw-West'	27%	6%	0%	24%
'07_Zuidoost'-'08_Westpoort'	30%	3%	0%	27%
'08_Westpoort'-'03_Oost'	10%	8%	0%	9%
'08_Westpoort'-'07_Zuidoost'	7%	12%	0%	6%

It is obvious from the graph that the car is the most attractive mode, and the aggregated travel time will therefore be almost equal to the travel times of this mode with a small reduction caused by the availability of the other modes. The observed standard deviations of the aggregated travel time are smaller than those of the car, as expected. The Logsum is largely influenced by the car travel times which becomes obvious both from the figure with averages as well as from the table with variation coefficients.

4.3.2 Travel Time Reliability over Days

The average travel times overs days are determined alongside the standard deviations for one time at each day: 9:00 am. The OD-relations were again divided into their distance classes as described in paragraph 4.1.1, so that the OD-relations can be compared with equivalent OD-relations of the same distance. The averages and standard deviations are visualized in Figure 4.5 for the short distances (<5km), in Figure 4.6 for the medium distances (5-10 km) and in Figure 4.7 for the long distances (>10km).

Short Distances

For the short distances (<5km), the average travel times and standard deviations over days are shown in Figure 4.5. It is noted that Public Transport is not very attractive for short distances, as the (averages of) the travel times a higher than those of the other modes, though this could be expected, and additionally have large deviations for some OD-relations. (Most notably ’04_Zuid’-‘05_West’, ‘05_West’-‘02_Noord’ and ‘05_West’-’08-Westpoort’. The corresponding connections in the other direction show smaller standard deviations, indicating less disruptions in that direction.

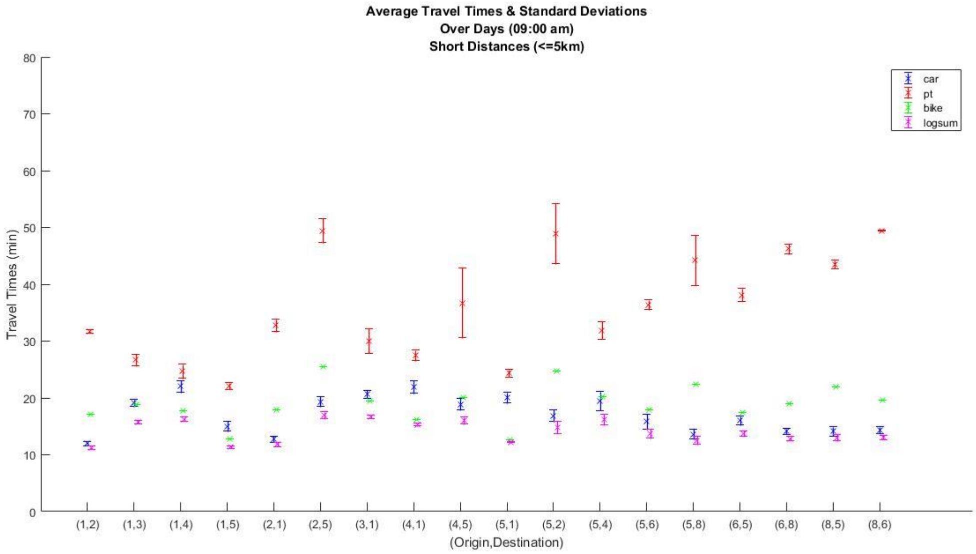


Figure 4.5 Average travel times with standard deviations for OD-relations short distances (<5 km) over days

The averages of the travel times for car and bike are for most short distance OD-relations comparable or within the same range. The standard deviations are small for car travel times and non-existent for bike travel times, due to being constant over time. The averages of the aggregated travel time (‘Logsum’) are lower than the averages of car, public transit and bike, which is in line with the expectation of the used aggregation method.

Table 4.12 Variation Coefficients for OD-relations short distances (<5 km) over days

	Car	PT	Bike	Logsum
'01_Centrum'-'02_Noord'	7%	2%	0%	5%
'01_Centrum'-'03_Oost'	7%	8%	0%	4%
'01_Centrum'-'04_Zuid'	10%	10%	0%	4%
'01_Centrum'-'05_West'	12%	5%	0%	5%
'02_Noord'-'01_Centrum'	8%	7%	0%	6%
'02_Noord'-'05_West'	9%	9%	0%	8%
'03_Oost'-'01_Centrum'	7%	14%	0%	4%
'04_Zuid'-'01_Centrum'	10%	7%	0%	3%
'04_Zuid'-'05_West'	11%	34%	0%	8%
'05_West'-'01_Centrum'	9%	6%	0%	2%
'05_West'-'02_Noord'	12%	22%	0%	14%
'05_West'-'04_Zuid'	17%	10%	0%	12%
'05_West'-'06_Nieuw-West’	17%	5%	0%	12%
'05_West'-'08_Westpoort'	13%	20%	0%	12%
'06_Nieuw-West’-'05_West'	10%	6%	0%	7%
'06_Nieuw-West’-'08_Westpoort'	7%	4%	0%	5%
'08_Westpoort'-'05_West'	12%	3%	0%	9%
'08_Westpoort'-'06_Nieuw-West’	8%	0%	0%	6%

In Table 4.12 the variation coefficients are given. It is noted that the relations originating from location '05_West' have high variation coefficients for the car and (thus) also for the Logsum, while travels originating from location '04_Zuid' have also (relatively) high variation coefficients for the mode car, though this does not result in high coefficients for the Logsum, because the standard deviations are much smaller for this (aggregated) ‘mode’. Trips from and to location '01_Centrum' have a low variation coefficient for the Logsum, due to the influence of the Bike.

Medium Distances

The average travel times and standard deviations over days for medium distances (5-10km) are shown in Figure 4.6. The results show the same pattern: high averages of public transit and low averages and standard deviations for car, then causing the aggregated travel time to be based largely on the car travel times.

The distribution of the averages over the OD-relations is very wide, some OD-relations have large averages while others have small averages. A possible explanation for this could be found in the fact that the distances between the OD-relations are still relatively high. If other distances classes were used, this might give a different impression.

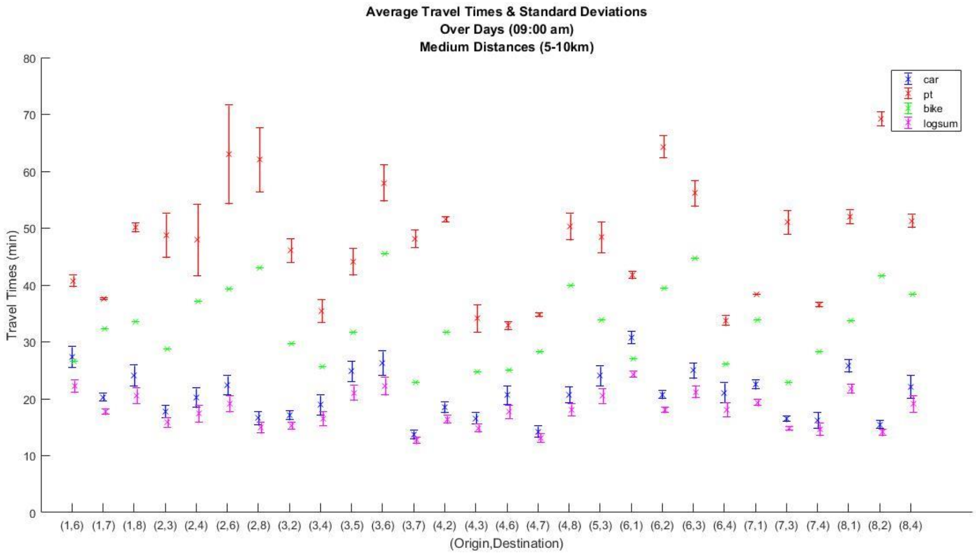


Figure 4.6 Average travel times with standard deviations for OD-relations medium distances (5-10 km) over days

The variation coefficients for these relations are given in Table 4.13. The variation coefficients for car and the Logsum are closely related, which is due to the Logsum being largely influenced by the car travel times.

Table 4.13 Variation Coefficients for OD-relations medium distances (5-10 km) over days

	Car	PT	Bike	Logsum
'01_Centrum'-'06_Nieuw-West’	13%	5%	0%	10%
'01_Centrum'-'07_Zuidoost'	6%	1%	0%	5%
'01_Centrum'-'08_Westpoort'	15%	3%	0%	14%
'02_Noord'-'03_Oost'	12%	16%	0%	10%
'02_Noord'-'04_Zuid'	17%	26%	0%	17%

	Car	PT	Bike	Logsum
'02_Noord'-'06_Nieuw-West’	15%	28%	0%	15%
'02_Noord'-'08_Westpoort'	14%	18%	0%	12%
'03_Oost'-'02_Noord'	10%	9%	0%	8%
'03_Oost'-'04_Zuid'	18%	11%	0%	15%
'03_Oost'-'05_West'	14%	11%	0%	12%
'03_Oost'-'06_Nieuw-West’	16%	11%	0%	14%
'03_Oost'-'07_Zuidoost'	11%	6%	0%	9%
'04_Zuid'-'02_Noord'	10%	2%	0%	9%
'04_Zuid'-'03_Oost'	12%	14%	0%	10%
'04_Zuid'-'06_Nieuw-West’	16%	5%	0%	13%
'04_Zuid'-'07_Zuidoost'	14%	2%	0%	11%
'04_Zuid'-'08_Westpoort'	13%	9%	0%	12%
'05_West'-'03_Oost'	15%	11%	0%	13%
'06_Nieuw-West’-'01_Centrum'	7%	3%	0%	4%
'06_Nieuw-West’-'02_Noord'	7%	6%	0%	6%
'06_Nieuw-West’-'03_Oost'	11%	8%	0%	10%
'06_Nieuw-West’-'04_Zuid'	17%	5%	0%	14%
'07_Zuidoost'-'01_Centrum'	7%	0%	0%	6%
'07_Zuidoost'-'03_Oost'	6%	8%	0%	5%
'07_Zuidoost'-'04_Zuid'	18%	2%	0%	15%
'08_Westpoort'-'01_Centrum'	9%	5%	0%	8%
'08_Westpoort'-'02_Noord'	10%	4%	0%	8%
'08_Westpoort'-'04_Zuid'	18%	4%	0%	16%

Long Distances

The average travel times and standard deviations over days for long distances (>10km) are shown in Figure 4.7. Due to the large distances, the bike travel times are high, of the same magnitude as the public transport times. The car travel times are lowest, thus influencing the aggregated travel time the most.

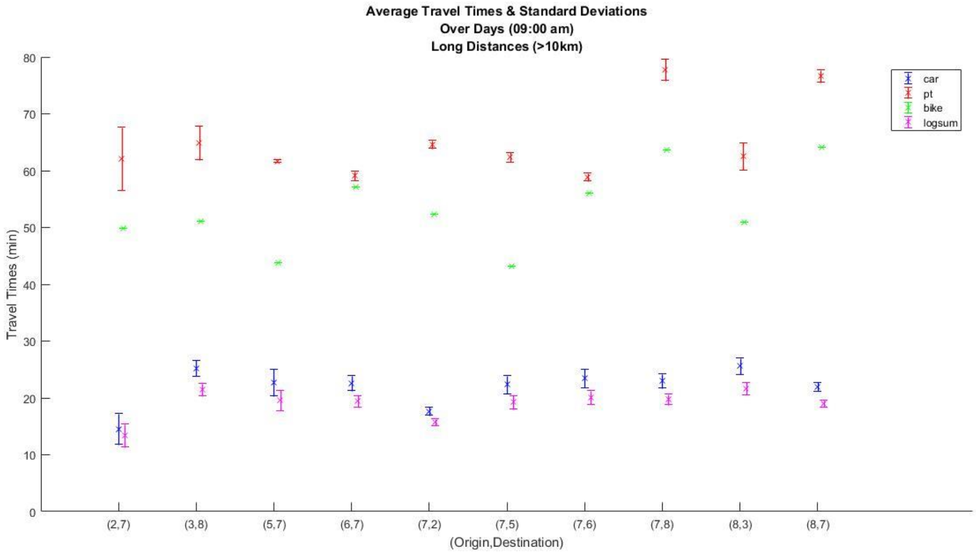


Figure 4.7 Average travel times with standard deviations for OD-relations long distances (>10 km) over days

Table 4.14 Variation Coefficients for OD-relations long distances (>10 km) over days

	Car	PT	Bike	Logsum
'02_Noord'-'07_Zuidoost'	37%	18%	0%	30%
'03_Oost'-'08_Westpoort'	11%	9%	0%	10%
'05_West'-'07_Zuidoost'	21%	1%	0%	18%
'06_Nieuw-West’-'07_Zuidoost'	12%	3%	0%	10%
'07_Zuidoost'-'02_Noord'	8%	2%	0%	7%
'07_Zuidoost'-'05_West'	14%	3%	0%	12%
'07_Zuidoost'-'06_Nieuw-West’	14%	2%	0%	12%
'07_Zuidoost'-'08_Westpoort'	11%	5%	0%	9%
'08_Westpoort'-'03_Oost'	11%	8%	0%	10%
'08_Westpoort'-'07_Zuidoost'	7%	3%	0%	6%

This is also confirmed by the variation coefficients given in Table 4.14. The values found for the Logsum are largely influenced by the values found for the car. These values are higher than those of the public transport, indicating that the public transport has more reliable travel times than those of the car (because of the lower standard deviation). In all fairness, this is not that surprising as the public transport generally follows a timetable and suffers less from disruptions due to other travellers, while the car travel times are highly sensitive for disruptions from those other travellers.

4.3.3 Reliability of the Accessibility within a Day

The variation in accessibility within a day is determined for the first Monday in the collected data: Monday March 27th 2017. The averages and standard deviations of the Potential Value and the SVIR Accessibility Indicator are shown in Figure 4.8 and Figure 4.9 respectively for each of the locations.

Potential Value

The averages and standard deviations of the Potential Value found for each of the origin locations within a day (March 27th) are shown in in Figure 4.8. The Potential Value can be interpreted as: "The higher the value, the better the accessibility".

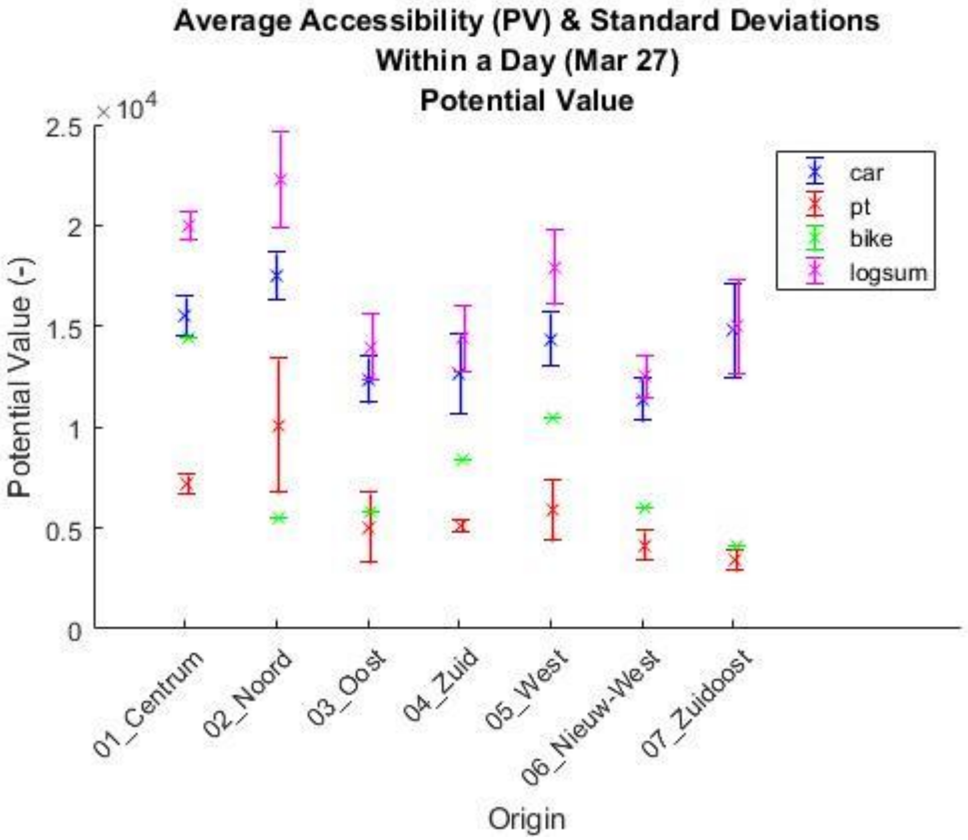


Figure 4.8 Average Accessibility (Potential Value) with standard deviations for Origins (1-7) within a day

Immediately, it can be seen that the Logsum has a higher Potential Value for all zones, indicating that taking all modalities/alternatives into account leads to a better accessibility according to the method (this was to be expected).

Origin '01_Centrum' has a high accessibility by bike and car, while the accessibility by public transit is much lower. This is remarkable, as a high accessibility by public transit is also expected since the location is located in the centre of Amsterdam. (This could be explained by the exclusion of short distance trips.) The standard deviation of the public transit accessibility is relatively low (compared to the other locations), indicating that the accessibility is very reliable over time.

The accessibility of origin locations '02_Noord', '03_Oost' and '05_West' are not very reliable as indicated by the relatively large standard deviations for this locations. Remarkably, the potential value of the Logsum is very high for location '02_Noord', likely due to the high potential value found for the car for this origin. Origin '02_Noord' is the only location which has an average potential value for bike which is lower than that of public transit, indicating that the accessibility by bike is relatively bad. This is due to bicycles having to cross the IJ with a ferry to reach this location.

For all origin locations, the Logsum is largely influenced by the car (which had the lowest travel times in general, and thus the highest accessibility was found). This is especially visible for origin locations '03_Oost', '04_Zuid', '06_Nieuw-West' and '07_Zuidoost'. All these locations are classified in paragraph 4.1.1 as being at the edge of the city.

For origin locations ‘03_Oost’, ‘04_Zuid’, ‘05_West’, ‘06_Nieuw-West’ and ‘07_Zuidoost’) the average potential value for public transit are the lowest, with locations ‘03_Oost’ and ‘05_West’ also having a large standard deviation, indicating that improvements are desired.

Origin ’06_Nieuw-West’ has the lowest average for the Logsum Potential Value, indicating that for this location the most can be gained by improvements. No Potential Value for Origin ‘08_Westpoort’ (the industrial area) was found, due to an error in the data collection: for many time points the travel time was not collected for this location.

Table 4.15 shows the variation coefficients, which is calculated by the ratio between the standard deviation and the average. Due to the high standard deviations for public transport in origins '02_Noord', '03_Oost' and '05_West', the variation coefficients for these locations are also very high. The Logsum is mostly influenced by the car.

Table 4.15 Variation Coefficients for the Reliability of the Accessibility (PV) within a day

	Car	PT	Bike	Logsum
'01_Centrum'	12%	13%	0%	7%
'02_Noord'	13%	66%	0%	21%
'03_Oost'	18%	69%	0%	24%
'04_Zuid'	31%	11%	0%	23%
'05_West'	18%	51%	0%	21%
‘06_Nieuw-West’	18%	35%	0%	17%
'07_Zuidoost'	32%	31%	0%	31%

SVIR Accessibility Indicator

The averages and standard deviations of the SVIR Accessibility Indicator found for each of the destination locations within a day (March 27th) are shown in Figure 4.9. The SVIR Accessibility Indicator is expressed in a speed [km/h]. This is the average speed with which trips to that destination are made. Higher speeds are more desirable, as it means that one’s destination is reached faster. However, due to the urban character of all the locations, it is expected that the average speeds will not become higher than 30 km/h.

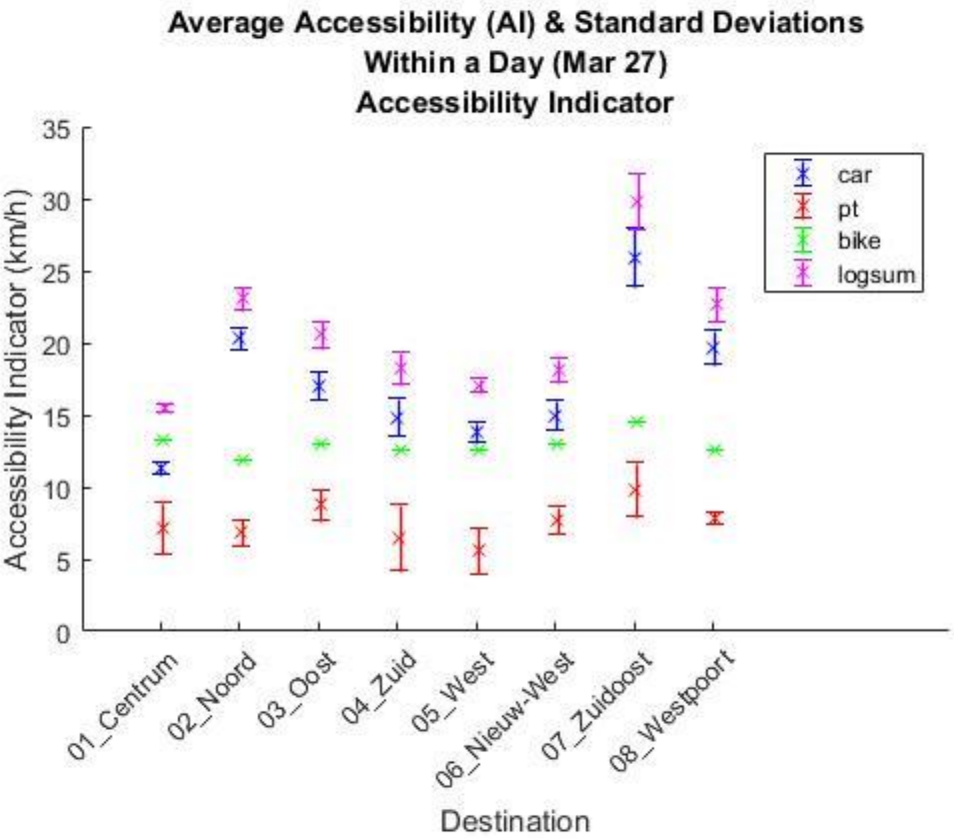


Figure 4.9 Average Accessibility (SVIR Accessibility Indicator) with standard deviations for Destinations (1-8) within a day

The average Logsum values for the SVIR Accessibility Indicator are all higher than the averages of the separate modes. This implies that combining the separate modes indeed gives a better accessibility than the accessibility per separate mode.

For all destinations, the SVIR Accessibility Indicator is lowest for public transit, as there the lowest (average) speeds can be found. However, the indicated average speeds are not surprising as average public transit speeds are generally not that high, due to the large amount of stops and access, egress and waiting times.

For destination location '01_Centrum' the average speeds are most alike over the different modalities, showing that for this location the modes are most equal. The destination locations located at the edge of the city ('02_Noord', '03_Oost', '04_Zuid', '06_Nieuw-West', '07_Zuidoost', '08_Westpoort') show the highest average speeds for car and (thus) the Logsum (as was to be expected). The standard deviation in the accessibility indicator of the Logsum is smaller than those of the other modes, due to the method that was used.

Due to its location, destination location '07_Zuidoost' has very high average speeds for car, and thus also for the Logsum (as this is hereby largely influenced by the speeds for car.

Remarkable is that destination '05_West' show a relatively bad accessibility for the SVIR Accessibility Indicator ('passive accessibility'), while it shows a good accessibility for the Potential Value ('active accessibility'). This illustrates the different perspectives of the accessibility indicators. Depending on what the policy perspective is, the indicator can be selected.

The variation coefficients are shown in Table 4.16. The Logsum is largely influenced by the car, and the variation coefficients for PT are very high due to the (relatively) large standard deviations of this mode.

Table 4.16 Variation Coefficients for the Reliability of the Accessibility (AI) within a day

	Car	PT	Bike	Logsum
'01_Centrum'	8%	50%	0%	3%
'02_Noord'	7%	26%	0%	7%
'03_Oost'	11%	25%	0%	9%
'04_Zuid'	17%	71%	0%	12%
'05_West'	10%	58%	0%	6%
‘06_Nieuw-West’	13%	25%	0%	9%
'07_Zuidoost'	16%	39%	0%	13%
'08_Westpoort'	12%	11%	0%	11%

4.3.4 Reliability of the Accessibility over Days

The reliability of the accessibility over days is determined for one time at each day: 9:00 am. The averages and standard deviations of the Potential Value and the SVIR Accessibility Indicator are shown in Figure 4.10 and Figure 4.11 respectively for each of the locations.

Potential Value

The averages and standard deviations of the Potential Value found for each of the origin locations over days (9:00 am) are shown in Figure 4.10.

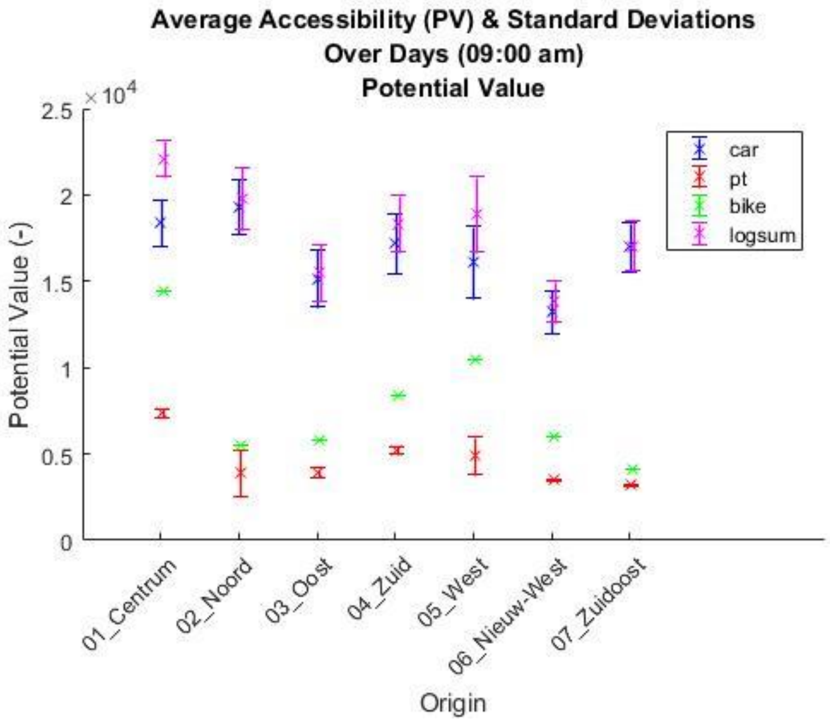


Figure 4.10 Average Accessibility (Potential Value) with standard deviations for Origins (1-7) over days

Also over multiple days, the potential value for the origin location ‘01_Centrum’ is highest, due to the high potential value for all of the separate modes.

For all of the origin locations the average potential value for the Logsum is higher than those of the separate modes, indicating that combining the modes indeed gives a better accessibility. However, for almost all origin locations the average Logsum accessibility is almost equal to the average car accessibility, so the added value is minimal. The Logsum is thus largely influenced by the car.

With the exception of origin ‘02_Noord’ the public transit shows a very reliable accessibility, as the standard deviations are minimal.

The standard deviations for the accessibly with the car were relatively high. This is likely due to the selected time during the morning peak. The deviations in the Logsum accessibility are hugely influenced by the deviations in the car accessibility.

Again, no Potential Value for origin ‘08_Westpoort’ (the industrial area) was found, due to an error in the data collection.

In Table 4.17, the variation coefficients are shown. The Logsum is highly dependent on the car, as shown in the figure and again confirmed by the variation coefficients in the table. The variation coefficients for public transit are small (with the exception of origin '02_Noord', which is the only region which has a relatively larger standard deviation) due to the low/almost non-existent standard deviations of the public transit.

Table 4.17 Variation Coefficients for the Reliability of the Accessibility (PV) over days

	Car	PT	Bike	Logsum
'01_Centrum'	15%	5%	0%	10%
'02_Noord'	17%	51%	0%	18%
'03_Oost'	23%	10%	0%	22%
'04_Zuid'	20%	7%	0%	18%
'05_West'	26%	4%	0%	20%
‘06_Nieuw-West’	18%	4%	0%	17%
'07_Zuidoost'	18%	3%	0%	17%

SVIR Accessibility Indicator

The reliability over days (9:00 am) of the SVIR Accessibility Indicator found for each of the destination locations is shown in Figure 4.11.

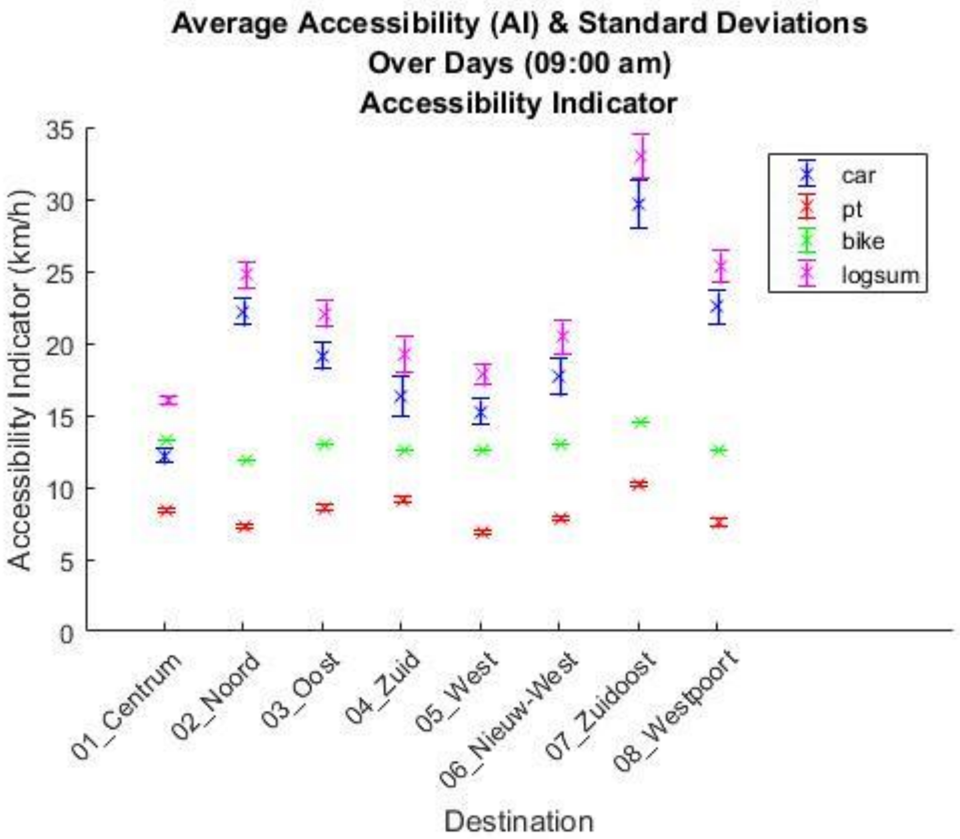


Figure 4.11 Average Accessibility (SVIR Accessibility Indicator) with standard deviations for Destinations (1-8) over days

The average Logsum values for the SVIR Accessibility Indicator are all higher than the averages of the separate modes. This implies that combining the separate modes indeed gives a better accessibility than the accessibility per separate mode.

For all destinations, the SVIR Accessibility Indicator is lowest for public transit, as there the lowest (average) speeds can be found. However, the indicated average speeds are not surprising as average public transit speeds are generally not that high, due to the large amount of stops.

For destination location ’01_Centrum’ the average speeds are most alike over the different modalities, showing that for this location the modalities are most equal. During peak hour (9:00 am) the accessibility by bike is better than the accessibility by car and public transit, due to lower average speeds of the latter two modes.

The destination locations located at the edge of the city (‘02_Noord’, ‘03_Oost’, ‘04_Zuid’, ‘06_Nieuw-West’, ‘07_Zuidoost’, ‘08_Westpoort’) show the highest average speeds for car and Logsum (as was to be expected), this is also the case for destination location ‘05_West’. Due to its location, destination location ‘07_Zuidoost’ has very high average speeds for car, and thus also for the Logsum (as this is hereby largely influenced by the speeds for car).

Surprisingly, destination location ‘05_West’ has the lowest public transit Accessibility of all the destinations. This location is located in the inner circle of the city, and therefore the public transit is expected to be better, like the Potential Value indicated. This shows the difference between the two approaches (‘passive accessibility’ vs. ‘active accessibility’).

Table 4.18 show the variation coefficients. The Logsum is highly dependent on the car, with the exception of destination '01_Centrum' which is largely influenced by the bike, as well as a little by the car.

Table 4.18 Variation Coefficients for the Reliability of the Accessibility (AI) over days

	Car	PT	Bike	Logsum
'01_Centrum'	8%	2%	0%	4%
'02_Noord'	8%	2%	0%	7%
'03_Oost'	10%	5%	0%	8%
'04_Zuid'	17%	3%	0%	13%
'05_West'	11%	5%	0%	8%
‘06_Nieuw-West’	14%	3%	0%	11%
'07_Zuidoost'	12%	2%	0%	10%
'08_Westpoort'	10%	2%	0%	8%

4.4 Conclusions Case Study

In this chapter the previously described method has been applied and tested in a case study for the city of Amsterdam. In this section conclusions are given on three subjects concerning the case study: application of theory, data collection and practical conclusions for Amsterdam.

4.4.1 Application of Theory

The case study shows that the previously proposed method is working in practice and gives consistent results that maintain the theoretical characteristics: the Logsum always gives travel times that are equal or lower than the travel times of the fastest mode. The same effect is observed by the reliability of the accessibility: the Logsum is always higher or equal to the accessibility of the best mode.

Considering multiple modes when determining the reliability provides insight for which mode improvements are most beneficial and should be done more often. The difference between the Logsum and the individual modes represents the additional value for travellers of having the option to choose between different modes. The Logsum values in comparison to one another could be used for a ranking of the locations / OD-relations amongst each other, though it is not advised to do so. The precise locations and distances between these locations are of large influence when comparing the locations / OD-relations and should therefore be taken into account, which is not done when comparing the numeric Logsum values.

Concerning the period for which the reliability is determined, the reliability within a day gives the most insight initially. After all, a reliable travel time (and accessibility) is desired at all hours of the day. Secondly, determining the reliability over days gives additional information whether the travel time (and accessibility) at a specific time is unreliable for this particular day only, indicating an incident, or over multiple days, which would indicate a structural problem.

Accessibility is normally calculated using a specific travel time. This travel time could be an average travel time or a travel time at a specific time point. By calculating the accessibility for each time point and then calculating the reliability of the accessibility, insight is gained in the effect of differing travel times on the accessibility and thus in the variation of the accessibility. The effect of different time points is shown on the accessibility. When more information on a specific location is wanted (for instance for the location with the lowest accessibility), the reliability of the travel times can be determined then for the OD-relations originating from or going to this location for additional insight into which OD-relations need improvement.

The accessibility indicators are expressed in different entities and therefore embody a different accessibility. The Potential Value is calculated with utilities and inhabitants. This measure is interpreted as: “the higher the better”. For this indicator it is very easy to compare the different modes with each other and with the Logsum, as all are expressed in the same entity. For the Logsum this means that the original Logsum formula as introduced by (Ben-Akiva & Lerman, 1985) is used. If the travel times would be used for the cost function, the differences between the Logsum and the other modes would become larger. The SVIR accessibility indicator is expressed as average speeds, where higher is also better. Comparing the different modes is more difficult due to the fact that each specific mode has a specific average speed which is accepted. The Logsum gives a value which lies above all of the average speeds of the separate modes. This can be interpreted as: there are more modes available as options, therefore the average travel time is *experienced* as faster than those of the separate modes by the traveller. However, this is a bit abstract and could be difficult to interpret.

4.4.2 Data Collection

Travel times were collected using the Google Maps Distance Matrix API. The Google Maps Distance Matrix API allows data to be collected over multiple modes and over multiple times, so that the travel time reliability and the reliability of the accessibility can be determined over multiple days and over multiple times during a day.

The Google Maps Distance Matrix API has advantages and disadvantages. The Google Maps API returns the expected travel times pre-trip instead of the realized travel times and also automatically selects the fastest route when multiple route options are available within a mode. This means it is unknown which route is used exactly at which moment, but at the same time it means that the route choice within a mode for a traveller is already done (with the underlying assumption that a traveller always chooses the fastest route). Consequently, it also means that extreme values were not present in the collected data, thus making this an unsuitable data source for determining robustness indicators. The reliability indicators used in this research are also influenced by the lack of these extreme values. However, as these extreme situations do not occur often, the absence of these values actually means that the reliability indicators are determined for normal everyday travel times, which is exactly what a traveller would do as well.

4.4.3 Practical conclusions for Amsterdam

For the city of Amsterdam the reliability of travel times and the reliability of the accessibility of 8 locations was determined. The aggregated travel time showed a lower average and smaller standard deviations. However, this was largely a result of the method that was used as the aggregated travel times over multiple modes are always lower than the travel times of the separate modes and the resulting averages and standard deviations will then also consequently be lower. The order of magnitude, or the difference between the Logsum and the rest of the modes, show the added value of having multiple alternatives available. The bigger this difference, the better the reliability.

Given the network, the results are plausible. The figures with the reliability of the accessibility show that location ‘01_Centrum’ is good accessible with public transport and bike and less with car, as was to be expected. The locations that lie on the edge on the city have mainly a high car accessibility, also due to the fast access to the ring road A10. Due to the larger distances to the other locations a lesser car and bike accessibility was found for these locations. This is especially visible for locations ‘02_Noord’ and ‘07_Zuidoost’.

Location ‘05_West’ lies halfway between the locations ‘01_Centrum’ and ‘06_Nieuw-West’, which is represented by a good bike accessibility. Locations ‘04_Zuid’, ‘06_Nieuw-West’ and ‘03_Oost’ show the bike accessibility (PV) consequently decreasing due to increasing distances to other locations. The SVIR Accessibility Indicator shows more or less constant average speeds for the bike. Locations ‘03_Oost’, ‘04_Zuid’ and ‘05_West’ are located near the ring A10 car ensuring a high car accessibility.

It becomes obvious from all locations that public transport is not an attractive mode if only travel time is considered. Most problematic are the large standard deviations for origin ‘02_Noord’ and ‘05_West’. For the Logsum (PV), the locations ‘03_Oost’, ‘04_Zuid’ and ‘06_Nieuw-West’ score the lowest and need attention. As the Logsum is largely influenced by the car for these locations, improvements in car and public transport networks are recommended to explore. Overall, the public transport networks needs most attention.

5 Conclusions & Recommendations

In this chapter the main conclusions and recommendations of this research are presented. This is done by answering the research questions (section 5.1) which were introduced in chapter 1. Afterwards, recommendations are given in section 5.2.

5.1 Conclusions

The goal of this research was to develop an assessment method for the reliability of travel times (on a route level) and the reliability of accessibility (on a zonal level) when single unimodal routes with alternatives over multiple modes are considered.

The main research question that needs to be answered is:

How can the reliability of travel times (on a route level) and the reliability of accessibility (on a zonal level) be assessed when single unimodal routes with alternatives over multiple modes are considered?

In order to answer this question, sub research questions were drawn up, which helped structure this research. These questions will be answered in paragraph 5.1.1, before the main research questions will be answered in paragraph 5.1.2. Additional conclusions concerning the case study are given in paragraph 5.1.3.

5.1.1 Answers to the Sub Research Questions

In this paragraph the answers to the sub research questions are given, so that in the next paragraph the main research question can be answered.

Reliability

For reliability, the following research question was drafted which will be answered below:

How can the reliability of travel times (on a route level) be determined?

Many studies were found concerning the subject of reliability. These have been addressed in section 2.1 along with several reliability indicators which are often used to determine the travel time reliability. In this research, it was chosen to use the Average (μ), the Standard Deviation (σ) and the Variation Coefficient (c_v) to determine the (travel time) reliability. These indicators were calculated for the separate modes, as well as for the aggregated travel time that was calculated with the Logsum method. Furthermore, two situations have been distinguished for which the reliability was determined:

- Reliability within a Day
- Reliability over Days

Comparing these two situations, it was concluded that the reliability within a day gives the most insight, as a reliable travel time is desired at all time points of a day. Reliability over days is complementary to the reliability within a day and is useful to determine if the unreliable travel times that occur at a specific time are due to an incident (only occurring at a particular day) or are a structural problem (recurring at multiple days).

In order to determine the reliability, travel times were collected for multiple time points. These time points were distributed over multiple moments within a day and also over multiple days. It has been deducted that collected data are better suited for this purpose than using data constructed by models, as models are already using averages which would not give the desired variability in the travel time distribution.

Considering multiple modes when determining the reliability provided insight into the differences in reliability between modes. It could then be deducted for which mode improvements are most needed. This should be done more often.

Accessibility

For accessibility two research questions were defined, which will be answered below.

How can the accessibility (on a zonal level) be determined?

The accessibility of a network was determined using the accessibility indicators found in literature and practice. In this research, two indicators were selected and used:

1. Hansen's Potential Value (Hansen, 1959);
2. SVIR Accessibility Indicator (Ministerie van Infrastructuur & Milieu, 2012).

These indicators were chosen because they determine accessibility in a different way. Hansen's Potential Value was calculated with utilities and inhabitants. The SVIR Accessibility Indicators was calculated using the travel times and the (crow fly) distances and expressed in average speeds. Both indicators were interpreted as 'higher is better'. However, with the SVIR indicator, the average speeds that are acceptable to users and policy makers differ per mode (e.g. users expect that the average speed for public transport is lower than for car), thus making it more difficult to compare the modes for this indicator.

How can the reliability of the accessibility (on a zonal level) be determined?

The reliability of the accessibility was determined using the same reliability indicators as for the travel time reliability: the Average (μ), the Standard Deviation (σ) and the Variation Coefficient (c_v). However, now the accessibility will be used as an input instead of the travel times.

Again, two situations can be distinguished: Reliability within a Day & Reliability over Days. For the Potential Value the utilities were used for the separate modes, allowing the original Logsum method to be used to calculated the PV over modes. For the SVIR accessibility indicator, the travel times were used for the separate modes and the aggregated travel time was used to determine the SVIR over modes.

Once the reliability of the accessibility, it was found which location had the worst accessibility. It is advised to then investigate the travel time reliability for the OD-relations originating from or going to this location, so that the worst OD-relations can be found and be improved purposefully.

Aggregation of Alternatives over Multiple Modes

For the aggregation of alternatives over multiple modes, the sub research question was:

Which aggregation methods can be used to aggregate travel times of alternatives over multiple modes?

Several aggregation methods were found in literature. The most theoretically accurate method was the Logsum method as introduced in (Ben-Akiva & Lerman, 1985). In chapter 3 it was investigated how this method could be used if different modes were used for the different alternatives.

It was possible to use the method as introduced by (Ben-Akiva & Lerman, 1985) over different modes, as the utilities of the modes were calculated and the Logsum method used utilities as well. However, the outcome of this method was expressed as an utility, while for the reliability a travel time was needed. Therefore, the Logsum method was rewritten so an “aggregated travel time” could be calculated.

The Logsum method provided a suitable foundation for the construction of an aggregated travel time provided that the numeric values for the parameters β_{LS} and ASC_{LS} (which are used to calculate the “aggregated travel time” out of the aggregated utility) are equal to that of the mode which has $ASC_m = 0$ and the highest absolute (numeric) value for β_m (compared to the β_m’s of the other modes).

That the Logsum always gives a better or just as good result as the best mode was illustrated in the case study. The difference between the Logsum and the individual modes (order of magnitude) represents the additional value for travellers of having the option to choose between different modes.

Data Collection at Multiple Time Points

Lastly, decisions for the collection of data at multiple time points were made based on the following research questions and answers.

Which data source(s) can be used to collect travel times for multiple modes at multiple time points?

In order to determine the reliability and the reliability of the accessibility, it was decided that the travel times should be collected for multiple time points. These time points should distributed over multiple moments within a day and also over multiple days. It was deducted that collected data is better suited for this purpose than using data constructed by models, as models are already using averages which would not give the desired variability in the travel time distribution

The Google Maps Distance Matrix API was selected because it enabled collecting data over multiple modes and over multiple times, so that the travel time reliability and the reliability of the accessibility could be determined over multiple days and over multiple times during a day.

What are the possibilities & limitations of these data sources?

The Google Maps Distance Matrix API had advantages and disadvantages. The Google Maps API returned the expected travel times pre-trip instead of the realized travel times and also automatically selected the fastest route when multiple route options were available within a mode. This meant that it was unknown which route was used exactly at which moment, but at the same time it meant that the route choice within a mode was already done.

Consequently, it also means that extreme values were not present in the collected data, thus making this an unsuitable data source for determining robustness indicators. The reliability indicators used in this research were also influenced by the lack of these extreme values. However, as these extreme situations do not occur often, the absence of these values actually means that the reliability indicators were determined for normal everyday travel times, which is exactly what a traveller would do as well.

5.1.2 Answer to the Main Research Question

In conclusion, this research has examined how the travel time reliability and the reliability of the accessibility over multiple modes could be determined. The travel time reliability and the reliability of the accessibility was determined with the Average (μ), the Standard Deviation (σ) and the Variation Coefficient (c_v) for two situations: 'Reliability within a day' and 'Reliability over days'.

As reliable travel times are desired at all moments of the day, the 'Reliability within a day' provides a better picture of the reliability than the 'Reliability over days'. The 'Reliability over days' can be used as an extension of the 'Reliability within a day' to provide additional insight in unreliable travel times.

To determine the reliability over multiple modes, the Logsum method is used as a basis for the "aggregated travel time over multiple modes", which combines the travel times of multiple modes into one value. The Logsum method gives a suitable foundation for this provided that the values for the parameters β_{LS} and ASC_{LS} were equal to the parameters of the mode with $ASC_m = 0$ and the highest (numeric) value for β_m.

5.1.3 Conclusions Case Study

For the city of Amsterdam the reliability of travel times and the reliability of the accessibility of 8 locations are determined. The aggregated travel time showed a lower average and smaller standard deviations. This was largely a result of the method that was used as the aggregated travel times over multiple modes are always lower than the travel times of the separate modes and the resulting averages and standard deviations will then also consequently be lower.

For the accessibility it was noted that the Potential Value determines an 'active accessibility' and the SVIR Accessibility Indicator determines a 'passive accessibility'. This distinction also has consequences for the result (see the results for location '05_West', which had a relatively good Potential Value, while a relatively bad SVIR Accessibility Indicator was found).

5.2 Recommendations

In this research, only travel time has been used as input for the determination of the reliability and the calculation of the accessibility, which allows comparison with currently used approaches. Though this is an important influence, other factors such as (generalized) costs or more specific socio-economic data (such as age, gender, income level, marital status, occupation, family size, etc) might also be relevant. It is recommended to investigate other factors that could add additional value.

Many accessibility indicators use the travel time of a specific mode to determine the accessibility of that mode as described in chapter 2. Multiple accessibility indicators have been identified and two indicators have been chosen for the calculation of the rest of the research. However, the two selected indicators outline two of the possibilities and it is dependent on the desired results which accessibility indicator is best to be selected. Specifically if other input variables besides travel time are used.

The Logsum method provides a stable and theoretically justified result. The resulting aggregated travel times is largely influenced by the fastest travel time. This provides an adequate result as the travel times are the only variables taken into account and are therefore very important. However, if other variables are taken into account and are deemed important as well, the Logsum method might not give the most desired results anymore. In that case it would be recommended to look for a other aggregation method.

In this research, two situations have been assumed: on one hand the travel time reliability & the (reliability of the) accessibility are determined per modality (which currently occupies a central position in practice), on the other hand the travel time reliability & the (reliability of the) accessibility are determined of all modalities together. An interesting scenario would be to study what would happen if one of the modes is unavailable. Due to the large portion in the modal split occupied by car, the unavailability of that mode would be most influential. It is expected that the other modes (public transport & bike) would then compensate for the absence of this mode and the next fastest mode would be decisive. This will likely give a different spatial pattern: other OD-relations might deserve attention and the ranking of the accessibility of the locations will probably differ.

Furthermore, the trips have been assumed to be unimodal (in which public transport has been dubbed as “one” mode) and all access and egress has been done by walking. For future research, this could be expanded with the inclusion of multimodal trips, where one mode would be used for the first part of the trip, before a transfer is made to another mode. The would give options to include bicycling as an access and/or egress mode for public transit or combine car and train (using P+R stations), for instance.

The case study was conducted for only a limited number of locations and OD-relations. For a more complete picture, it is recommended to extend the number of locations (and thus the number of OD-relations as well). This extension can be done for both the number of locations inside the city of Amsterdam (so a higher density is reached) and the number of locations outside of the city of Amsterdam (so a larger region is covered).

6 References

Ben-Akiva, M., & Lerman, S. (1985). *Discrete Choice Analysis: Theory and Application to Travel Demand.* Cambridge, Massachusetts: The Massachusetts Institute of Technology.

Billington, R., & Allan, R. N. (1992). *eliability evaluation of engineering systems: Concepts.* New York: Plenum Press.

Chen, A., Yang, H., Lo, H. K., & Tang, W. H. (2002). Capacity reliability of a road network: an assessment methodology and numerical results. *Transportation Research Part B*, 225-252.

Clark, S., & Watling, D. (2005). Modelling network travel time reliability under stochastic. *Transportation Research Part B*, 119-140.

de Boer, C. (2014). *Travel Time Reliability and Quality Assesment of a Route Set through Route Aggregation.* Delft: TU Delft.

Gemeente Amsterdam. (2013). *Amsterdam Aantrekkelijk Bereikbaar.* Amsterdam: Gemeente Amsterdam.

Geurs, K. T., & van Wee, B. (2004). Accessibility Evaluation of Land-Use and Transport Strategies: Review and Research Directions. *Journal of Transport Geography*, 127-140.

Google. (2016, June 12). *Google Maps*. Retrieved from Google Maps: https://maps.google.com/

Google Developers. (2017, January 10). *Google Maps Distance Matrix API*. Retrieved from Google Developers: https://developers.google.com/maps/documentation/distance-matrix/

Hägerstrand, T. (1970). What about people in regional science? *Ninth European Congress of the Regional Science Association* (pp. 7-21). Regional Science Association.

Hansen, W. G. (1959). How Accessibility Shapes Land Use. *Journal of the American Institute of Planners, 25*(2), 73-76. Retrieved from http://www.tandfonline.com/doi/citedby/10.1080/01944365908978307?scroll=top&needAccess=true

Immers, B., Egeter, B., Snelder, M., & Tampere, C. (2011). Reliability of Travel Times and Robustness of Transport Networks. In M. Kutz, *Handbook of Transportation Engineering, Volume I: Systems and Operations* (pp. 3.1 - 3.29). New York: McGraw-Hill Education.

Ingram, D. (1971). The concept of accessibility: A search for an operational form . *Regional Studies*, 101-107.

Knoop, V., Snelder, M., van Zuylen, H., & Hoogendoorn, S. (2012). Link-level vulnerability indicators for real-world networks. *Transportation Research Part A*, 843–854.

Kutz, M. (2011). *Handbook of Transportation Engineering* (2 ed., Vol. I: Systems and Operations). McGraw-Hill Education.

MathWorks. (2016). MATLAB. Benelux.

Metropoolregio Amsterdam. (2016, June). *Over MRA*. Retrieved from Metropoolregio Amsterdam: http://www.metropoolregioamsterdam.nl/over-mra

Metropoolregio Amsterdam. (2016). *Ruimtelijke-economische Actie-Agenda 2016 - 2020.* Amsterdam: Metropoolregio Amsterdam.

Ministerie van Infrastructuur & Milieu. (2012). *Structuurvisie Infrastructuur & Ruimte.* Den Haag: Ministerie van Infrastructuur & Milieu.

Ministerie van Infrastructuur & Milieu. (2012). *Structuurvisie Infrastructuur & Ruimte.* Den Haag: Ministerie van Infrastructuur & Milieu.

Ministerie van Infrastructuur en Milieu. (2012). *IenM maakt ruimte.* Den Haag: Ministerie van Infrastructuur en Milieu.

Ministerie van Infrastructuur en Milieu. (2014). *De SVIR bereikbaarheidsindicator.*

Onderzoek, Informatie en Statistiek. (2016). *Stadsdelen in cijfers 2016.* Amsterdam: Gemeente Amsterdam.

Pieters, M., van den Elshout, J., & Herder, J. (2014). Verkeersmodel Amsterdam: Ontwikkeling van een Nieuw Stedelijk Model. *Colloquium Vervoersplanologisch Speurwerk* (p. 15). Eindhoven: Goudappel; Significance.

REISinformatiegroep B.V. (2017, august 15). *9292 reist met je mee*. Retrieved from 9292.nl: https://9292.nl/

SHRP2. (2014). *Incorporating Travel Time Reliability into the Highway Capacity Manual.* Washington D.C.: Transportation Research Board.

SHRP2. (n.d.). *SHRP2 Reliability Reports (L03, L07, L08).* SHRP2.

Snelder, M., Calvert, S., & Minderhoud, M. (2014). *Robuust Mobiliteitsysteem.* Delft: TNO.

Snelder, M., van Zuylen, H., & Immers, L. (2012). A framework for robustness analysis of road networks for short term variations in supply. *Transportation Research Part A*, 828–842.

van Lint, J., & van Zuylen, H. (2005). Monitoring and predicting freeway travel time reliability. *84th Meeting of the Transportation research Board*, (pp. 54-62). Washington D.C.

Wakabayashi, H., & Iida, Y. (1992). Upper and Lower Bounds of Terminal Reliability of Road Networks: An Efficient Method with Boolean Algebra. *Journal of Natural Disaster Science, 14*(1), 29-44.

A Travel Time Distributions

To get an idea of the course of the collected travel times over a day and to show them in relation to the travel times of other modes, the collected travel times for driving, public transit and bicycling are plotted over time.

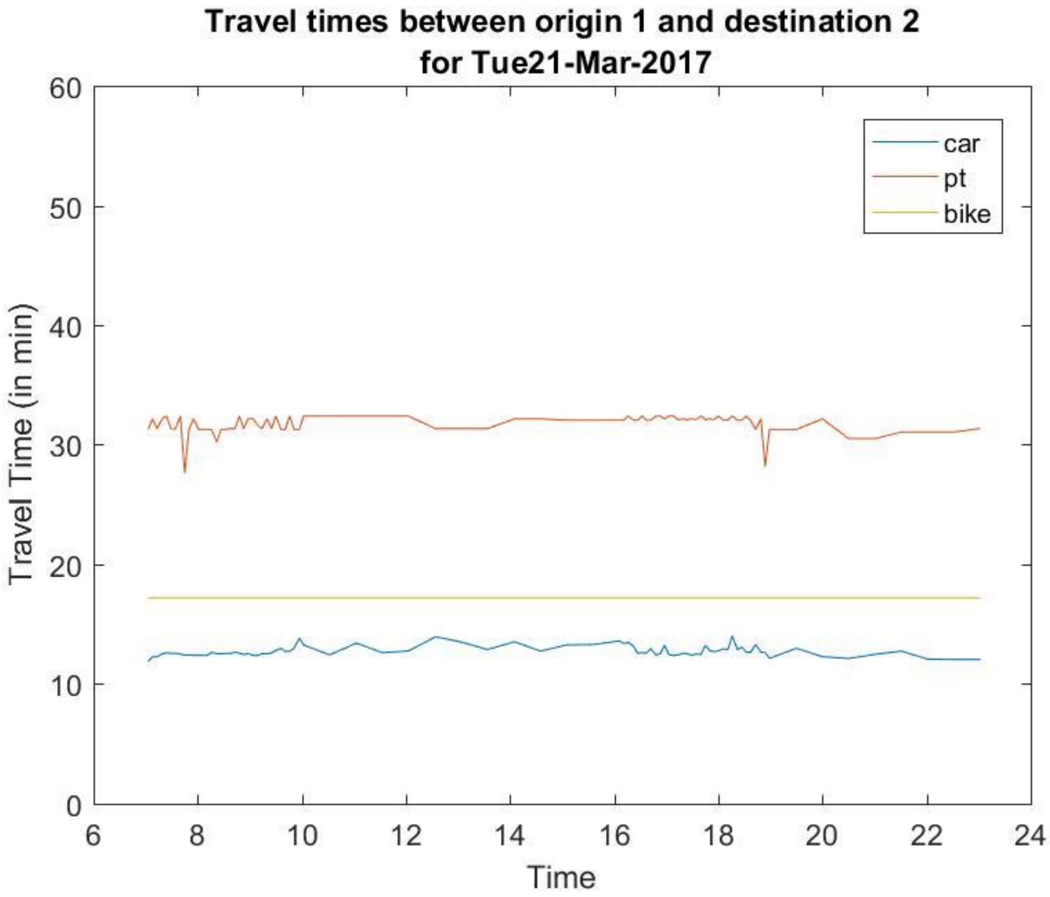
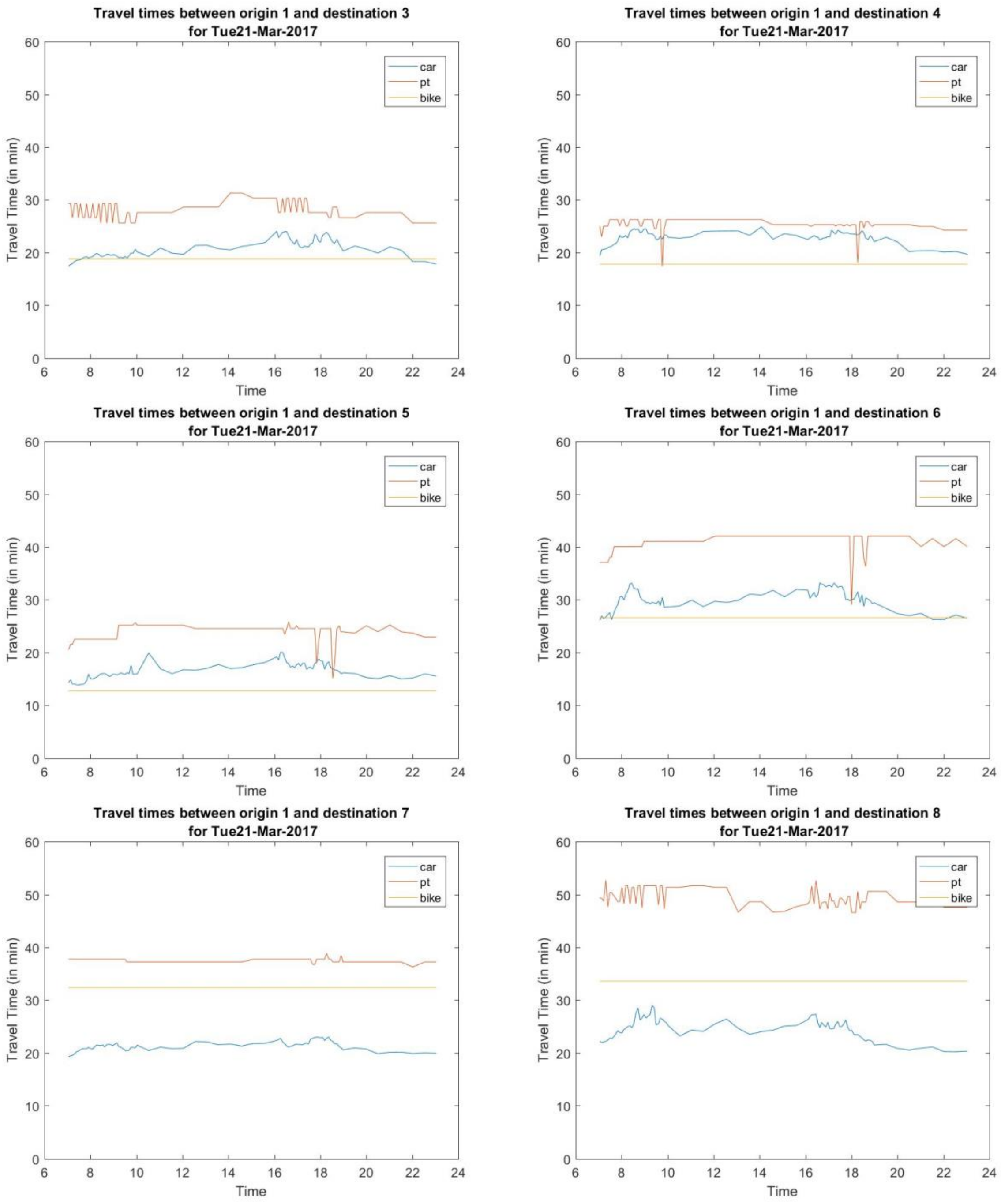


Figure A.1 Travel times for trips between origin location 1 and destination location 2 on Tuesday March 21 feb 2017

In Figure A.1, the collected travel times are shown for the trips from origin 1 to destinations 2 on Tuesday March 21st 2017. Figure A.2 shows similar (smaller) figures with the trips from origin 1 to destinations 3, 4, 5, 6, 7 and 8 respectively on Tuesday March 21st 2017. The same was done for the other origin zones, as well as the other days. These graphs are not shown here, however, because the extra figures would show similar graphs.


Travel times between origin 1 and destination 3 for Tue21-Mar-2017

Travel times between origin 1 and destination 4 for Tue21-Mar-2017

Travel times between origin 1 and destination 5 for Tue21-Mar-2017

Travel times between origin 1 and destination 6 for Tue21-Mar-2017

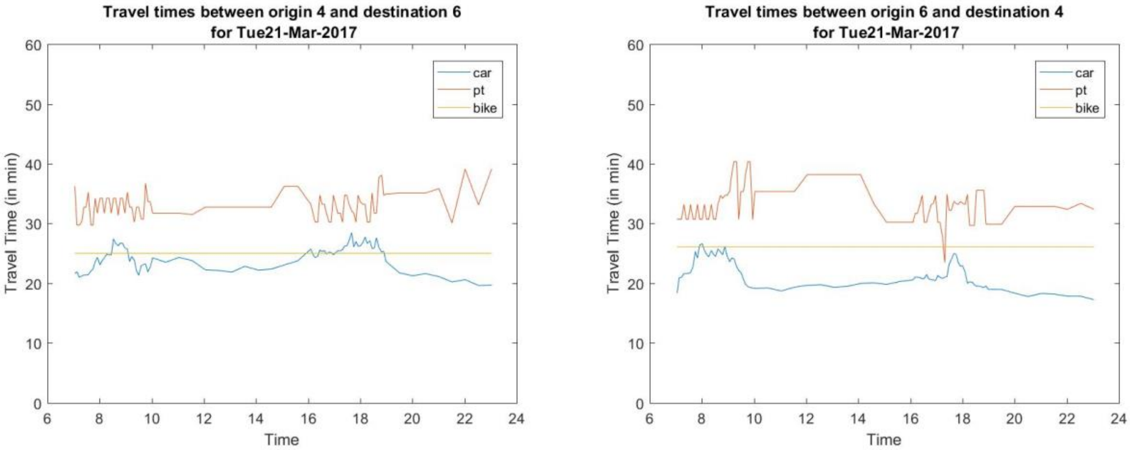
Travel times between origin 1 and destination 7 for Tue21-Mar-2017

Travel times between origin 1 and destination 8 for Tue21-Mar-2017

Figure A.2 Travel times for trips between origin location 1 and destination locations 3 - 8 on Tuesday March 21 feb 2017

The graphs in Figure A.1 and Figure A.2 show that, logically, the travel times between origin 1 (‘Centrum’) and the surrounding areas 3 (‘Oost’), 4 (‘Zuid’) and 5 (‘West’) lie close together, while for the other areas the differences between the travel times are higher, due to the larger distances between the zones.

For the mode driving there is a slight increase in the travel times during the peak hours (7:00 – 9:00 for the morning peak & 16:00-18:30 for the evening peak), though this is not overtly clear from the graphs in Figure A.1 & Figure A.2, as it contains the graphs with trips from origin zone 1 (‘Centrum’). In Figure A.3 this can be seen more obvious, where the graphs for the trips between zones 4 (‘Zuid’) and 6 (‘Nieuw-West’) are shown. These graphs further illustrate that the predicted travel times for the outward trip differ from the travel times of the return trip and the travel times between two zones are thus not interchangeable.


Travel times between origin 4 and destination 6 for Tue21-Mar-2017

Travel times between origin 6 and destination 4 for Tue21-Mar-2017

Figure A.3 Travel times for trips between origin/destination zones 4 and 6 on Tuesday March 21 feb 2017

B Quality of Collected Public Transit Data

Although it is expected that the travel times for public transport are higher than those for the car, the differences between the public transport times and the travel times of the other modes (car and bike) seem very high in the collected data (based on the travel time distributions given in Appendix A). This raises the question what the quality of the public transport data of the Google Maps API is.

Therefore, the public transit travel times collected with the Google Maps Distance Matrix API are compared with the travel times found with the regular Google Maps (Google, 2016) (it is expected that these will be equal as the same data would be used) and the 9292 website (REISinformatiegroep B.V., 2017). The detected travel times for each of the sources are given in the tables below and will be compared for each OD-relation.

During this analysis, it was revealed that the location from origin/destination ‘07_Zuidoost’ was not found as an origin/destination at the 9292-website. No data has thus been collected for this location in the 9292 column. The comparison with location ‘07_Zuidoost’ as an origin location has therefore not been done for the other sources either.

In Table B.1 the travel times originating from origin ’01_Centrum’ are given. Comparing the travel times from different sources shows that the travel times are much alike, with only small deviations (1 to 3 minutes at the most).

Table B.1 Comparison for PT travel times for OD-pairs originating in origin '01_Centrum'

Origin	Destination	Date	Time	API	Maps	9292
'01_Centrum'	'02_Noord'	Thu 3-8-2017	17:41	33 min	34 min	35 min
'01_Centrum'	'03_Oost'	Thu 3-8-2017	17:48	29 min	29 min	27 min
'01_Centrum'	'04_Zuid'	Thu 3-8-2017	17:48	26 min	26 min	24 min
'01_Centrum'	'05_West'	Thu 3-8-2017	17:50	25 min	27 min	27 min
'01_Centrum'	‘06_Nieuw-West’	Thu 3-8-2017	17:54	42 min	40 min	39 min
'01_Centrum'	'07_Zuidoost'	Thu 3-8-2017	17:59	38 min	35 min	x
'01_Centrum'	'08_Westpoort'	Thu 3-8-2017	18:00	48 min	49 min	48 min

Table B.2 Comparison for PT travel times for OD-pairs originating in origin '02_Noord'

Origin	Destination	Date	Time	API	Maps	9292
'02_Noord'	'01_Centrum'	Thu 3-8-2017	18:26	34 min	34 min	32 min
'02_Noord'	'03_Oost'	Thu 3-8-2017	18:29	45 min	48 min	42 min
'02_Noord'	'04_Zuid'	Thu 3-8-2017	18:31	1u 2min	1 u	45 min
'02_Noord'	'05_West'	Thu 3-8-2017	18:46	47 min	45 min	46 min
'02_Noord'	‘06_Nieuw-West’	Thu 3-8-2017	18:38	1u 4min	1 u	59 min
'02_Noord'	'07_Zuidoost'	Thu 3-8-2017	18:46	1u 7min	1u 1min	x
'02_Noord'	'08_Westpoort'	Thu 3-8-2017	18:26	1u 12min	1 u 12min	1u 11min

In Table B.2 the travel times originating from origin ’02_Noord’ are given. Comparing the travel times from different sources shows that most travel times are alike, with differences of a couple of minutes. Remarkably, for OD-relation ‘02_Noord’-‘04_Zuid’ the website 9292 finds a public transport travel time which is 15 minutes shorter than the travel time found with Google Maps or the Google Maps API. This is caused by the default settings of the search engines: 9292 gives the options with the shortest travel time, while Google also minimizes the number of transfers. In this particular OD-relations, 9292 has found an option with an extra transfer (making the total number of transfers for this trip: 2), which Google does not give.

Table B.3 Comparison for PT travel times for OD-pairs originating in origin '03_Oost'

Origin	Destination	Date	Time	API	Maps	9292
'03_Oost'	'01_Centrum'	Thu 3-8-2017	18:47	30 min	29 min	35 min
'03_Oost'	'02_Noord'	Thu 3-8-2017	18:45	45 min	48 min	44 min
'03_Oost'	'04_Zuid'	Thu 3-8-2017	18:47	35 min	35 min	31 min
'03_Oost'	'05_West'	Thu 3-8-2017	18:47	48 min	49 min	51 min
'03_Oost'	‘06_Nieuw-West’	Thu 3-8-2017	18:50	1u	58 min	58 min
'03_Oost'	'07_Zuidoost'	Thu 3-8-2017	18:47	58 min	46 min	x
'03_Oost'	'08_Westpoort'	Thu 3-8-2017	19:03	1u 6min	1u 5min	1u 5min

Table B.3 shows the travel times for public transport for the OD-pairs originating from origin ‘03_Oost’. Most travel times are in the same order size, though for the relations '03_Oost'-'01_Centrum' the Google data has found a travel times 5/6 minutes shorter than 9292. For the relation '03_Oost'-'07_Zuidoost' no 9292 data has been found, though Google Maps and the Google Maps API return different travel times already. A cause for these differences was not found, (at another time these differences were much smaller.

In Table B.4 the comparison is made for the travel times of OD-pairs originating from origin ‘04_Zuid’. Most travel times are similar, with a deviation of 1 or 2 minutes. The exceptions are OD-pairs '04_Zuid'-’06_Nieuw-West’ and '04_Zuid'-'08_Westpoort', where 9292 has found travel times which are 8/11 minutes and 18/17 minutes lower than the Google Maps. In the first case, the differences are caused by differences in access and egress times: the walking times are slightly different (indicating different speeds), plus the departure time is different. Google takes the exact time the request is made as departure time (which will thus also include waiting times); 9292 takes the minimum travel/walking time, thus varying the departure time. This is also the explanation for the second case: 9292 optimizes the travel time to a minimum and shifts the departure time slightly to a later time, while Google takes the departure time as set, which causes longer waiting times on the way.

Table B.4 Comparison for PT travel times for OD-pairs originating in origin ‘04_Zuid’

Origin	Destination	Date	Time	API	Maps	9292
'04_Zuid'	'01_Centrum'	Thu 3-8-2017	19:00	26 min	26 min	27 min
'04_Zuid'	'02_Noord'	Thu 3-8-2017	19:00	53 min	52 min	50 min
'04_Zuid'	'03_Oost'	Thu 3-8-2017	19:15	31 min	32 min	32 min
'04_Zuid'	'05_West'	Thu 3-8-2017	19:04	31 min	32 min	33 min
'04_Zuid'	‘06_Nieuw-West’	Thu 3-8-2017	19:04	41 min	44 min	33 min
'04_Zuid'	'07_Zuidoost'	Thu 3-8-2017	19:15	35 min	35 min	x
'04_Zuid'	'08_Westpoort'	Thu 3-8-2017	18:56	59 min	58min	41 min

Table B.5 shows the comparison between PT travel times which have origin location ‘05_West’. All relations have at most 1-4 minutes deviation from the other sources.

Table B.5 Comparison for PT travel times for OD-pairs originating in origin '05_West'

Origin	Destination	Date	Time	API	Maps	9292
'05_West'	'01_Centrum'	Thu 3-8-2017	19:16	23 min	22 min	22 min
'05_West'	'02_Noord'	Thu 3-8-2017	19:21	54 min	51 min	50 min
'05_West'	'03_Oost'	Thu 3-8-2017	19:12	51 min	51 min	46 min
'05_West'	'04_Zuid'	Thu 3-8-2017	19:12	35 min	34 min	33 min
'05_West'	'06_Nieuw-West'	Thu 3-8-2017	19:14	38 min	37min	36 min
'05_West'	'07_Zuidoost'	Thu 3-8-2017	19:11	1u 4min	1u 2min	x
'05_West'	'08_Westpoort'	Thu 3-8-2017	19:26	43 min	42 min	41 min

In Table B.6 the travel times of the different sources are given for the OD-relations starting at origin '06_Nieuw-West'. For relation '06_Nieuw-West'-'02_Noord', Google Maps gives a large deviation compared to the other sources. Google and 9292 give completely different itineraries. While they start out the same, Google uses the train and then a bus, while 9292 immediately takes the bus. It is possible that 9292 also takes the costs of a trip into account (these are given for each itinerary, while this is not visible in Google). Another possibility would be that 9292 and Google take different walking speeds into account, causing one of the sources to think a transfer is not possible, while the other would give this option. No information on the walking speeds was found, however, so this is just speculation.

Table B.6 Comparison for PT travel times for OD-pairs originating in origin '06_Nieuw-West'

Origin	Destination	Date	Time	API	Maps	9292
'06_Nieuw-West'	'01_Centrum'	Thu 3-8-2017	19:21	41 min	39 min	38 min
'06_Nieuw-West'	'02_Noord'	Thu 3-8-2017	19:21	1u 7min	54 min	1u 5min
'06_Nieuw-West'	'03_Oost'	Thu 3-8-2017	19:31	57 min	56 min	57 min
'06_Nieuw-West'	'04_Zuid'	Thu 3-8-2017	19:31	37 min	36 min	35 min
'06_Nieuw-West'	'05_West'	Thu 3-8-2017	19:26	38 min	36 min	36 min
'06_Nieuw-West'	'07_Zuidoost'	Thu 3-8-2017	19:31	1u 3min	1u 1min	x
'06_Nieuw-West'	'08_Westpoort'	Thu 3-8-2017	19:29	48 min	46 min	45 min

Table B.7 Comparison for PT travel times for OD-pairs originating in origin '08_Westpoort'

Origin	Destination	Date	Time	API	Maps	9292
'08_Westpoort'	'01_Centrum'	Thu 3-8-2017	19:54	56 min	54 min	49 min
'08_Westpoort'	'02_Noord'	Thu 3-8-2017	19:54	1u 15min	1u 12min	60min
'08_Westpoort'	'03_Oost'	Thu 3-8-2017	19:54	1u 3min	1u 2min	1u 2min
'08_Westpoort'	'04_Zuid'	Thu 3-8-2017	19:54	58 min	58 min	57 min
'08_Westpoort'	'05_West'	Thu 3-8-2017	19:54	45 min	44 min	42 min
'08_Westpoort'	'06_Nieuw-West'	Thu 3-8-2017	19:55	48 min	47 min	46 min
'08_Westpoort'	'07_Zuidoost'	Thu 3-8-2017	19:55	1u 9min	1u 12min	x

The comparison for the travel times for OD-pairs starting in origin '08_Westpoort'are given in Table B.7. For the OD-pair '08_Westpoort'-'01_Centrum', the travel times found in 9292 are 7/5 minutes shorter than those of Google. For the OD-relation '08_Westpoort'-'02_Noord' these differences are even bigger: 15/12 minutes. The cause for these differences, could not be uncovered.

C Choice for Utility Function in Case Study

The aggregation of travel times over multiple modes has been done with using utility theory as described by (Ben-Akiva & Lerman, 1985). For the utility function four options are distinguished, which will influence the outcome of the aggregated travel time and the modal split. The four options which are distinguished are:

- Utility function with fixed β and no ASC;
- Utility function with fixed β and mode-dependent ASC (ASC_m);
- Utility function with mode-dependent β (β_m) and no ASC);
- Utility function with mode-dependent β (β_m) and mode-dependent ASC (ASC_m).

The values for the parameters have been estimated so that a reasonable Modal Split is found. It is noted that these are purely based on the researchers (expert) judgment as no data on the actual modal split on the level of OD-relations (which was the level that the travel times were collected at) could be found. The parameters were estimated for the data collected at (Monday) March 20th 2017 at 12:00.

With a fixed β and no ASC, the utility functions looks as follows and the values for the parameters are given in Table C.1:

$$V_{od,m,t} = \beta * TT_{od,m,t} \tag{C.1}$$

Table C.1 Values for parameters β

Parameter	Value [-]
$\boldsymbol{\beta}$	-0,3

With these parameters the modal split is based purely on the travel times of the different modes (shown in the column 'Modal Split 1' in Table C.5). High travel times for Public Transit were found, so the percentages for this mode is low on all relations. The aggregated travel times are always lower than the travel times of the fastest alternative for each OD-destination (the column 'Difference with Agg.TT' in Table C.5 show values all smaller than 0) , which was to be desired so that method was stable. The modal split shows a preference for the car, and in some cases for the bike. With additional parameters, these values are changed.

With a fixed β and a mode dependent ASC_m, the utility functions looks as follows and the values for the parameters are given in Table C.2:

$$V_{od,m,t} = ASC_m + \beta * TT_{od,m,t} \tag{C.2}$$

Table C.2 Values for parameters β and ASC_m

Parameter	Value [-]	Parameter	Value [1/min]
$\boldsymbol{ASC_{car}}$	0	β	-0,3
$\boldsymbol{ASC_{pt}}$	2		
$\boldsymbol{ASC_{bike}}$	0,5		

Using these parameters results in a different modal split, shown in the column 'Modal Split 2' in Table C.5. Most notable is that for the relation '07_Zuidoost' to '01_Centrum' now public transit has the highest percentage of the modal split for that relation. The relation does have a direct metro-connection and has therefore a relatively fast travel time (compared to other OD-relations for public transport). The rest of the OD-relations have a modal split which is mostly divided over car and bike. For the OD-relations that include areas on the outskirts of the city usually higher percentages can be found for car, while the OD-relations which include areas in the centre have higher percentages for bike. The method is still stable as indicated by the last three columns Table C.5.

The utility function is adapted as to better express the valuation of a traveller for the travel time of a certain mode. Therefore, the parameter β is expressed per mode. For the bike, it will cost the traveller extra effort, therefore the valuation of said mode will be lower than for the mode car, where the traveller does not need to make this effort. In public transport, the traveller does not need to pay as much attention, so they can undertake other activities. Therefore, this valuation will be (although slightly) higher than that for the car mode. This results in the parameters as described below.

With a mode-dependent β (β_m) and no ASC, the utility function looked as follows and the values for the parameters are given in Table C.3:

$$V_{od,m,t} = \beta_m * TT_{od,m,t} \tag{C.3}$$

Table C.3 Values for parameters $\boldsymbol{\beta_m}$

Parameter	Value [1/min]
$\boldsymbol{\beta_{car}}$	-0,3
$\boldsymbol{\beta_{pt}}$	-0,25
$\boldsymbol{\beta_{bike}}$	-0,4

With these parameters a modal shift can be detected towards car and public transit for the examined OD-relations, due to the high β_{bike} (see the column 'Modal Split 3' in Table C.6). The modal split is extremely in favor of the car, this can be amended by adding the Alternative Specific Constants (ASC), which is done next.

With a mode-dependent β (β_m) and a mode dependent ASC_m, the utility functions looks as follows and the values for the parameters are given in Table C.4:

$$V_{od,m,t} = ASC_m + \beta_m * TT_{od,m,t} \tag{C.4}$$

Table C.4 Values for parameters $\boldsymbol{\beta_m}$ and $\boldsymbol{ASC_m}$

Parameter	Value [-]	Parameter	Value [1/min]
$\boldsymbol{ASC_{car}}$	-1	$\boldsymbol{\beta_{car}}$	-0,3
$\boldsymbol{ASC_{pt}}$	-3	$\boldsymbol{\beta_{pt}}$	-0,25
$\boldsymbol{ASC_{bike}}$	0	$\boldsymbol{\beta_{bike}}$	-0,4

With these parameters the modal split becomes more distributed over the modes, as shown in the column 'Modal Split 4' in Table C.6. For the majority of the OD-relations the car stays the dominant mode, due to the location of the areas and the favorable travel times compared to the other modalities. The other relations show a high percentage for the bike. Almost all of these relations are either originating from or going to location ‘01_Centrum’ (which can be easily reached by bike) or one of the other central locations (locations ‘04_Zuid’, ’05_West’, ‘06_Nieuw-West‘).

Concluding, on the influence of the values for the parameters β & ASC it can be said that:

- The values for the parameters are dependent on the data and will influence the outcomes.
- The values for the parameters are of large influence on the outcomes of the modal split and the Logsum / aggregated travel time. As long as the largest β_m is selected to calculate the aggregated travel time (for the mode m with $ASC_m = 0$), as described in chapter 3 the method is stable. Using one of the other parameter values results in outcomes that might be higher than the minimum travel time of the separate modes, thus making the method instable and theoretically incorrect.
- Choosing other values for the parameters will affect the results as well: Choosing other parameters will give a different modal split, as already indicated by the exploration on the different forms of the utility function, and will cause the Logsum value to take on another value as well. This in turn effects the aggregated travel time.

It was chosen to use the most “complete” utility function which (according to the researchers judgement) gave the most plausible modal split. This is the utility function with mode-dependent β (β_m) and mode-dependent ASC (ASC_m) with the parameters given in Table C.4:

$$V_{od,m,t} = ASC_m + \beta_m * TT_{od,m,t} \qquad (C.5)$$

Table C.5 Overview of OD-relations with collected travel times and modal splits for utility functions with fixed β and no ASC (case 1) or mode-specific ASC (ASC_m; case 2)

		Travel Times (in min)			Modal Split 1			Logsum 1	Agg.TT 1	Difference with min.TT		Modal Split 2			Logsum 2	Agg.TT 2	Difference with min.TT
Origin	Destination	TT_car	TT_pt	TT_bike	Car	PT	Bike					Car	PT	Bike			
1	2	16,82	32,40	17,20	53%	0%	47%	-4,403	14,676	-2,141		39%	3%	58%	-4,113	13,711	-3,105
1	3	22,20	27,62	18,82	25%	5%	70%	-5,285	17,616	-1,201		14%	21%	65%	-4,713	15,712	-3,105
1	4	23,50	25,27	17,80	14%	8%	78%	-5,087	16,958	-0,842		7%	30%	63%	-4,378	14,594	-3,206
1	5	18,17	24,55	12,78	16%	2%	81%	-3,629	12,098	-0,685		10%	10%	80%	-3,110	10,368	-2,416
1	6	32,50	42,18	26,58	14%	1%	85%	-7,811	26,035	-0,548		9%	4%	87%	-7,340	24,467	-2,116
1	7	23,20	35,87	32,37	92%	2%	6%	-6,877	22,924	-0,276		79%	13%	8%	-6,720	22,401	-0,799
1	8	32,42	48,82	33,60	59%	0%	41%	-9,189	30,631	-1,785		45%	2%	52%	-8,932	29,773	-2,643
2	1	12,22	26,92	17,97	84%	1%	15%	-3,491	11,636	-0,581		72%	6%	21%	-3,340	11,134	-1,082
2	3	21,58	43,28	28,72	89%	0%	11%	-6,362	21,208	-0,375		83%	1%	16%	-6,289	20,962	-0,622
2	4	22,35	50,60	37,13	99%	0%	1%	-6,693	22,310	-0,040		98%	0%	2%	-6,684	22,280	-0,070
2	5	21,32	49,40	25,47	78%	0%	22%	-6,142	20,473	-0,844		68%	0%	32%	-6,005	20,018	-1,299
2	6	36,82	73,93	39,27	68%	0%	32%	-10,653	35,511	-1,306		56%	0%	44%	-10,462	34,875	-1,942
2	7	15,98	62,78	49,87	100%	0%	0%	-4,795	15,983	0,000		100%	0%	0%	-4,795	15,983	0,000
2	8	32,95	72,23	43,02	95%	0%	5%	-9,837	32,791	-0,159		93%	0%	7%	-9,808	32,692	-0,258
3	1	24,82	28,70	19,38	16%	5%	80%	-5,586	18,621	-0,763		9%	20%	72%	-4,984	16,612	-2,771
3	2	23,07	53,43	29,73	88%	0%	12%	-6,793	22,643	-0,423		82%	0%	18%	-6,718	22,393	-0,674
3	4	26,40	36,38	25,58	43%	2%	55%	-7,075	23,584	-2,000		29%	11%	61%	-6,674	22,247	-3,336
3	5	31,97	49,12	31,67	48%	0%	52%	-8,848	29,494	-2,173		35%	2%	63%	-8,544	28,479	-3,188
3	6	41,52	63,72	45,47	77%	0%	23%	-12,187	40,624	-0,893		66%	1%	33%	-12,041	40,135	-1,382
3	7	18,23	56,03	22,80	80%	0%	20%	-5,244	17,479	-0,755		70%	0%	30%	-5,120	17,067	-1,167
3	8	41,73	56,53	51,10	93%	1%	6%	-12,450	41,502	-0,232		84%	7%	8%	-12,349	41,164	-0,570
4	1	25,98	25,38	16,17	5%	6%	90%	-4,741	15,802	-0,365		2%	21%	76%	-4,077	13,589	-2,577
4	2	28,92	54,03	31,70	70%	0%	30%	-8,314	27,714	-1,203		58%	0%	42%	-8,133	27,110	-1,806
4	3	23,20	30,87	24,73	58%	6%	36%	-6,411	21,370	-1,830		36%	27%	37%	-5,937	19,790	-3,410
4	5	23,20	29,47	20,10	27%	4%	69%	-5,655	18,851	-1,249		16%	18%	66%	-5,118	17,062	-3,038
4	6	27,55	32,20	25,03	30%	7%	63%	-7,048	23,495	-1,538		16%	29%	55%	-6,418	21,394	-3,639
4	7	22,62	35,62	28,27	83%	2%	15%	-6,599	21,998	-0,618		69%	10%	21%	-6,412	21,373	-1,244
4	8	37,15	49,02	39,92	68%	2%	30%	-10,763	35,878	-1,272		52%	11%	37%	-10,488	34,960	-2,190
5	1	23,25	24,75	12,65	4%	2%	94%	-3,729	12,430	-0,220		2%	10%	87%	-3,160	10,535	-2,115
5	2	28,35	51,70	24,67	25%	0%	75%	-7,114	23,712	-0,954		17%	0%	83%	-6,716	22,386	-2,281
5	3	31,43	45,38	33,83	67%	1%	32%	-9,023	30,077	-1,356		52%	6%	42%	-8,780	29,268	-2,166
5	4	25,00	30,82	20,20	19%	3%	78%	-5,814	19,382	-0,818		11%	14%	75%	-5,275	17,585	-2,615
5	6	17,95	37,77	17,97	50%	0%	50%	-4,693	15,643	-2,307		38%	1%	62%	-4,407	14,689	-3,261
5	7	35,60	58,82	43,83	92%	0%	8%	-10,598	35,326	-0,274		87%	1%	12%	-10,543	35,144	-0,456
5	8	15,67	44,48	22,33	88%	0%	12%	-4,573	15,243	-0,424		82%	0%	18%	-4,498	14,992	-0,675

		Travel Times (in min)			Modal Split 1			Logsum 1	Agg.TT 1	Difference with min.TT		Modal Split 2			Logsum 2	Agg.TT 2	Difference with min.TT
Origin	Destination	TT_car	TT_pt	TT_bike	Car	PT	Bike					Car	PT	Bike			
6	1	37,22	41,22	27,12	5%	1%	94%	-8,074	26,913	-0,203		3%	6%	91%	-7,545	25,149	-1,968
6	2	53,13	72,15	39,47	2%	0%	98%	-11,824	39,412	-0,055		1%	0%	99%	-11,330	37,766	-1,701
6	3	35,77	52,85	44,82	93%	1%	6%	-10,660	35,534	-0,232		87%	4%	9%	-10,588	35,292	-0,475
6	4	27,23	33,97	26,13	40%	5%	55%	-7,244	24,148	-1,986		23%	23%	54%	-6,718	22,392	-3,741
6	5	19,47	41,90	17,37	35%	0%	65%	-4,783	15,942	-1,425		24%	0%	75%	-4,428	14,760	-2,607
6	7	35,02	59,28	57,12	100%	0%	0%	-10,503	35,010	-0,007		99%	1%	0%	-10,498	34,993	-0,024
6	8	16,47	49,02	19,07	69%	0%	31%	-4,563	15,209	-1,258		57%	0%	43%	-4,377	14,589	-1,877
7	1	34,20	38,75	33,88	42%	11%	47%	-9,403	31,345	-2,539		21%	40%	39%	-8,712	29,041	-4,842
7	2	32,95	66,32	52,37	100%	0%	0%	-9,882	32,940	-0,010		99%	0%	0%	-9,880	32,933	-0,017
7	3	19,50	48,15	22,87	73%	0%	27%	-5,539	18,464	-1,036		62%	0%	37%	-5,379	17,929	-1,571
7	4	23,85	37,08	28,37	78%	1%	20%	-6,911	23,035	-0,815		64%	9%	27%	-6,707	22,358	-1,492
7	5	39,87	61,80	43,18	73%	0%	27%	-11,644	38,815	-1,052		62%	1%	38%	-11,478	38,259	-1,608
7	6	46,33	59,20	56,10	93%	2%	5%	-13,828	46,094	-0,239		80%	13%	7%	-13,682	45,606	-0,727
7	8	52,68	76,02	63,67	96%	0%	4%	-15,768	52,559	-0,124		94%	1%	6%	-15,739	52,465	-0,219
8	1	36,97	49,25	33,78	28%	1%	72%	-9,802	32,675	-1,108		18%	3%	78%	-9,391	31,302	-2,481
8	2	33,25	67,23	41,63	93%	0%	7%	-9,897	32,991	-0,259		88%	0%	12%	-9,850	32,832	-0,418
8	3	35,85	57,50	50,93	99%	0%	1%	-10,743	35,809	-0,041		97%	1%	2%	-10,726	35,755	-0,095
8	4	27,23	53,62	38,35	97%	0%	3%	-8,135	27,116	-0,118		94%	0%	6%	-8,110	27,035	-0,199
8	5	16,07	42,12	21,98	85%	0%	14%	-4,663	15,544	-0,523		78%	0%	22%	-4,571	15,238	-0,829
8	6	16,72	49,80	19,55	70%	0%	30%	-4,659	15,530	-1,186		59%	0%	41%	-4,481	14,938	-1,779
8	7	35,03	75,07	64,05	100%	0%	0%	-10,510	35,033	-0,001		100%	0%	0%	-10,510	35,032	-0,001

Table C.6 Overview of OD-relations with collected travel times and modal splits for utility functions with mode-specific β (β_m) and no ASC (case 3) or mode-specific ASC (ASC_m; case 4)

		Travel Times (in min)			Modal Split 3			Logsum 3	Agg.TT 3	Difference with min.TT		Modal Split 4			Logsum 4	Agg.TT 4	Difference with min.TT
Origin	Destination	TT_car	TT_pt	TT_bike	Car	PT	Bike					Car	PT	Bike			
1	2	16,82	32,40	17,20	83%	4%	13%	-4,857	12,143	-4,674		69%	0%	30%	-5,680	14,200	-2,616
1	3	22,20	27,62	18,82	45%	36%	19%	-5,870	14,675	-4,142		44%	5%	51%	-6,850	17,124	-1,692
1	4	23,50	25,27	17,80	25%	52%	23%	-5,660	14,150	-3,650		26%	7%	66%	-6,711	16,777	-1,023
1	5	18,17	24,55	12,78	34%	17%	48%	-4,384	10,961	-1,823		21%	1%	78%	-4,866	12,165	-0,618
1	6	32,50	42,18	26,58	54%	24%	22%	-9,127	22,817	-3,766		46%	3%	51%	-9,968	24,921	-1,662
1	7	23,20	35,87	32,37	88%	12%	0%	-6,832	17,079	-6,121		98%	2%	1%	-7,935	19,838	-3,362
1	8	32,42	48,82	33,60	90%	8%	2%	-9,622	24,056	-8,361		93%	1%	6%	-10,650	26,626	-5,791
2	1	12,22	26,92	17,97	93%	4%	3%	-3,592	8,979	-3,238		92%	1%	7%	-4,582	11,455	-0,762
2	3	21,58	43,28	28,72	98%	1%	1%	-6,456	16,139	-5,444		98%	0%	2%	-7,455	18,638	-2,945
2	4	22,35	50,60	37,13	100%	0%	0%	-6,702	16,755	-5,595		100%	0%	0%	-7,704	19,260	-3,090
2	5	21,32	49,40	25,47	98%	0%	2%	-6,370	15,925	-5,391		94%	0%	6%	-7,335	18,338	-2,979
2	6	36,82	73,93	39,27	99%	0%	1%	-11,035	27,588	-9,229		97%	0%	3%	-12,020	30,049	-6,768
2	7	15,98	62,78	49,87	100%	0%	0%	-4,795	11,987	-3,996		100%	0%	0%	-5,795	14,487	-1,496
2	8	32,95	72,23	43,02	100%	0%	0%	-9,884	24,710	-8,240		100%	0%	0%	-10,883	27,208	-5,742
3	1	24,82	28,70	19,38	33%	43%	24%	-6,332	15,829	-3,554		32%	6%	63%	-7,290	18,225	-1,159
3	2	23,07	53,43	29,73	99%	0%	1%	-6,912	17,279	-5,788		98%	0%	2%	-7,901	19,753	-3,314
3	4	26,40	36,38	25,58	71%	22%	7%	-7,578	18,945	-6,638		76%	3%	21%	-8,649	21,624	-3,960
3	5	31,97	49,12	31,67	90%	6%	4%	-9,482	23,705	-7,962		88%	1%	11%	-10,464	26,159	-5,507
3	6	41,52	63,72	45,47	97%	3%	0%	-12,421	31,053	-10,463		99%	0%	1%	-13,442	33,605	-7,911
3	7	18,23	56,03	22,80	97%	0%	3%	-5,444	13,610	-4,623		93%	0%	7%	-6,402	16,004	-2,229
3	8	41,73	56,53	51,10	83%	17%	0%	-12,338	30,845	-10,888		97%	3%	0%	-13,492	33,731	-8,002
4	1	25,98	25,38	16,17	11%	47%	42%	-5,594	13,985	-2,182		8%	5%	87%	-6,324	15,809	-0,357
4	2	28,92	54,03	31,70	97%	1%	2%	-8,649	21,623	-7,294		95%	0%	5%	-9,626	24,064	-4,853
4	3	23,20	30,87	24,73	66%	31%	3%	-6,540	16,349	-6,851		83%	5%	12%	-7,771	19,427	-3,773
4	5	23,20	29,47	20,10	50%	33%	17%	-6,264	15,660	-4,440		50%	4%	46%	-7,260	18,151	-1,949
4	6	27,55	32,20	25,03	41%	51%	7%	-7,384	18,459	-6,574		61%	10%	29%	-8,770	21,924	-3,109
4	7	22,62	35,62	28,27	88%	11%	1%	-6,662	16,655	-5,962		96%	2%	3%	-7,740	19,351	-3,266
4	8	37,15	49,02	39,92	75%	25%	1%	-10,854	27,135	-10,015		94%	4%	2%	-12,081	30,201	-6,949
5	1	23,25	24,75	12,65	10%	22%	68%	-4,674	11,685	-0,965		5%	2%	93%	-4,992	12,480	-0,170
5	2	28,35	51,70	24,67	79%	1%	20%	-8,267	20,668	-3,998		59%	0%	41%	-8,975	22,439	-2,228
5	3	31,43	45,38	33,83	86%	13%	1%	-9,278	23,196	-8,237		94%	2%	4%	-10,367	25,918	-5,515
5	4	25,00	30,82	20,20	42%	34%	24%	-6,635	16,587	-3,613		38%	4%	58%	-7,532	18,830	-1,370
5	6	17,95	37,77	17,97	85%	1%	14%	-5,218	13,044	-4,906		69%	0%	31%	-6,013	15,032	-2,918
5	7	35,60	58,82	43,83	98%	2%	0%	-10,661	26,653	-8,947		99%	0%	0%	-11,675	29,187	-6,413
5	8	15,67	44,48	22,33	98%	0%	1%	-4,684	11,710	-3,957		96%	0%	4%	-5,661	14,153	-1,514

		Travel Times (in min)			Modal Split 3			Logsum 3	Agg.TT 3	Difference with min.TT		Modal Split 4			Logsum 4	Agg.TT 4	Difference with min.TT
Origin	Destination	TT_car	TT_pt	TT_bike	Car	PT	Bike					Car	PT	Bike			
6	1	37,22	41,22	27,12	21%	50%	29%	-9,609	24,022	-3,094		20%	6%	74%	-10,544	26,360	-0,756
6	2	53,13	72,15	39,47	44%	5%	51%	-15,112	37,780	-1,686		24%	0%	76%	-15,508	38,771	-0,696
6	3	35,77	52,85	44,82	92%	8%	0%	-10,649	26,623	-9,144		99%	1%	0%	-11,717	29,292	-6,475
6	4	27,23	33,97	26,13	55%	40%	6%	-7,567	18,918	-7,215		73%	7%	20%	-8,851	22,128	-4,005
6	5	19,47	41,90	17,37	75%	1%	25%	-5,547	13,868	-3,499		53%	0%	47%	-6,198	15,495	-1,871
6	7	35,02	59,28	57,12	99%	1%	0%	-10,492	26,229	-8,787		100%	0%	0%	-11,503	28,758	-6,259
6	8	16,47	49,02	19,07	94%	0%	6%	-4,873	12,184	-4,283		84%	0%	16%	-5,770	14,425	-2,041
7	1	34,20	38,75	33,88	36%	63%	1%	-9,227	23,067	-10,816		75%	18%	8%	-10,967	27,417	-6,467
7	2	32,95	66,32	52,37	100%	0%	0%	-9,884	24,709	-8,241		100%	0%	0%	-10,885	27,212	-5,738
7	3	19,50	48,15	22,87	96%	0%	4%	-5,812	14,529	-4,971		91%	0%	9%	-6,754	16,885	-2,615
7	4	23,85	37,08	28,37	88%	11%	1%	-7,028	17,569	-6,281		95%	2%	4%	-8,099	20,248	-3,602
7	5	39,87	61,80	43,18	97%	3%	0%	-11,925	29,813	-10,054		98%	0%	1%	-12,943	32,357	-7,510
7	6	46,33	59,20	56,10	71%	29%	0%	-13,559	33,897	-12,437		95%	5%	0%	-14,846	37,115	-9,218
7	8	52,68	76,02	63,67	96%	4%	0%	-15,765	39,412	-13,271		99%	1%	0%	-16,799	41,998	-10,685
8	1	36,97	49,25	33,78	72%	21%	6%	-10,766	26,914	-6,869		78%	3%	19%	-11,843	29,606	-4,177
8	2	33,25	67,23	41,63	100%	0%	0%	-9,973	24,932	-8,318		100%	0%	0%	-10,971	27,429	-5,821
8	3	35,85	57,50	50,93	97%	3%	0%	-10,729	26,821	-9,029		100%	0%	0%	-11,751	29,378	-6,472
8	4	27,23	53,62	38,35	99%	1%	0%	-8,164	20,410	-6,824		100%	0%	0%	-9,167	22,918	-4,315
8	5	16,07	42,12	21,98	98%	0%	2%	-4,798	11,995	-4,071		95%	0%	5%	-5,770	14,424	-1,642
8	6	16,72	49,80	19,55	94%	0%	6%	-4,956	12,389	-4,327		86%	0%	14%	-5,863	14,657	-2,060
8	7	35,03	75,07	64,05	100%	0%	0%	-10,510	26,274	-8,759		100%	0%	0%	-11,510	28,775	-6,258