

Travel Time Reliability and Quality Assessment of a Route Set through Route Aggregation

C.W. (Chris) de Boer



Master of Science Thesis

Travel Time Reliability and Quality Assessment of a Route Set through Route Aggregation

MASTER OF SCIENCE THESIS

For the degree of Master of Science in Civil Engineering at Delft
University of Technology

C.W. (Chris) de Boer

June 16, 2014

Available at <http://repository.tudelft.nl>

Faculty of Civil Engineering and Geosciences · Delft University of Technology

TNO

The work in this thesis was supported by TNO: Netherlands Organization for Applied Scientific Research. Their cooperation and support is hereby gratefully acknowledged.

 **TU Delft** Delft
University of
Technology

Copyright © Civil Engineering
All rights reserved.

DELFT UNIVERSITY OF TECHNOLOGY
DEPARTMENT OF
CIVIL ENGINEERING

The undersigned hereby certify that they have read and recommend to the Faculty of
Civil Engineering and Geosciences for acceptance a thesis entitled

TRAVEL TIME RELIABILITY AND
QUALITY ASSESSMENT OF A ROUTE SET THROUGH ROUTE AGGREGATION

by

C.W. (CHRIS) DE BOER

in partial fulfillment of the requirements for the degree of
MASTER OF SCIENCE CIVIL ENGINEERING

Dated: June 16, 2014

Supervisor(s):

Prof.dr.ir. B. van Arem

Dr.ir. R. van Nes

Dr. M. Snelder, *TNO*

Committee member(s):

Dr.ir F.H.L.R. Clemens, *Water Management*

Ir. P.B.L. Wiggeraad, *Thesis Coordinator*

Preface

This thesis is the final result of my graduation as a Master of Science at the Delft University of Technology at the faculty of Civil Engineering and Geosciences. The research described in this master thesis has been carried out while being a graduation intern at research institute TNO in Delft, the Netherlands for the duration of 8 months in the years 2013 and 2014.

This project originated from the fact that despite the increase in car traffic in the world and the importance of reliable networks, to date there has been little agreement on how to evaluate and improve network reliability. In addition, no research was found that surveyed reliability on the scale of a network, making it interesting to determine whether an evaluation on such a scale was possible and useful.

First off, I would like to thank my graduation committee, lead by prof. dr. ir. Bart van Arem from the Transport and Planning department, and furthermore consisting of dr. ir. Rob van Nes from the Transport and Planning department, Maaïke Snelder from TNO, dr. ir. Francois Clemens from the Water Management department and ir. Paul Wiggenraad, the Transport and Planning master coordinator. They have provided me with constructive remarks and have monitored my work from the very beginning.

Special thanks go out to TNO and Maaïke Snelder, who have provided me with the opportunity and means to carry out this research, which included helping me to find a concrete research subject, providing the necessary data and facilities and being a great daily supervisor. I also would like to thank the others at the Smart Mobility department, who have been kind and helpful. In particular I would like to thank Michiel Minderhoud, who has provided me with the route set generation algorithm and has helped me to adjust it for the purposes of this thesis.

From the TU Delft, I would like to thank Rob van Nes for being my daily supervisor and for always being critical and constructive regarding my work, so that I could make the best out of this project.

Finally, I would like to thank anyone who has helped me in any way to accomplish this research project and whom I have not mentioned yet.

Summary

Abstract

Conventional travel time reliability assessment focuses either on reliability on route level or the determination of the valuation of reliability in route choice. However, a connection between origin and destination usually consists of multiple routes, thereby providing the option to choose. This study assesses the reliability and quality of the aggregate of the route set of an *OD*-pair as having (an) alternative(s) can compensate for deterioration of a single route. Furthermore, it is unknown how the perception of reliability of the aggregate of available routes depends on the travel behavior of the user. An adapted Logsum is proposed as aggregation method and the perceived reliability is investigated for multiple scenarios. It is determined that the Logsum is an appropriate measure for aggregation, but should be used combined with the ratio between number of alternatives and dispersion. The perceived reliability analysis showed that informing travelers and variable departure times can significantly improve the user perceived travel time reliability.

Keywords: Travel time reliability; Travel time variability; Travel time reliability measures; Route aggregation; Logsum; Connection assessment; Departure time choice

Introduction

The reliability of road networks is of great significance, as a large share of personal and business transport movements is by road and the prospect of suffering delay on the network is undesired from every perspective. The road networks in and around urban environments are often dense and extensively used. An efficient and reliable functioning of the road network in these areas is of critical importance as many users depend on it.

Conventionally, the analysis of network performance is based on the estimation and evaluation of average conditions (speed, travel times or generalized costs) for a given time period for a specific network element (e.g. road segments and routes). Based on averaged terms, an implication can be provided regarding the functioning of a network element, yet it can be said that an averaged indicator does not reflect on the variation of that indicator. Furthermore,

the focus is on network elements such as roads and routes, thereby missing the network perspective of the actual connection between two locations. Besides the network perspective, the effect of variation of conditions directly affects the user and how it uses the network. Consistent and significant variation of network conditions may lead to unexpected costs to the user, either in time or money. As such, the user is unable to rely on the network and may change his travel behavior.

We can indicate travel time reliability of separate routes, thereby ascertaining a corresponding travel time distribution from which the travel time reliability can be derived. Although this process can be done for all routes in the route set of the connection separately, no specific indication for the quality of the route set can be derived from this with current methodology described in literature. From a network perspective, ascertaining a measure to determine the aggregate of routes in the route set and their collective properties is desirable in order to be able to assess the quality of the connection. An illustration is presented in figure 1.

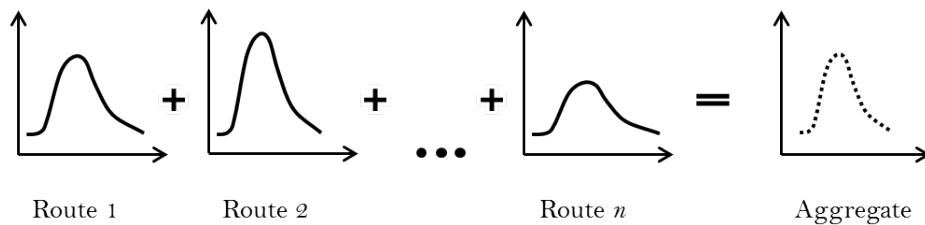


Figure 1: Exemplary illustration of route aggregation.

From a user perspective, route travel time reliability can only be perceived after taking the route a number of times and thereby experiencing the variations in travel time. As such, users that are unfamiliar with the connection between the origin and destination are thus also unfamiliar with the optional routes and their specifics, such as travel time and travel time reliability. They may have no initial perception of the reliability of the travel time of the routes in the route set and therefore their travel behavior may be different from a user who is familiar with the connection. An example for traveler using a single route and a traveler that occasionally alters his route is illustrated in figure 2.

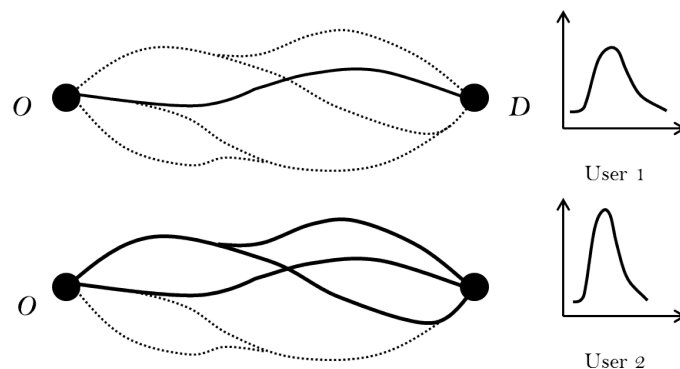


Figure 2: Illustration of different route choices and how that affects the travel time distribution.

In other words, we can determine the travel time reliability of separate routes and the influence

on route choice, but there is no method yet to determine how route choice determines the perceived reliability of the connection between the *OD*-pair.

The objective of the research reported in this thesis is to give insight in the assessment of a set of routes in a connection, thereby aggregating routes and their collective properties. The main contribution of this thesis is divided into in a theoretical basis and a practical application. The theoretical basis comprises two parts. The first is to select and test an aggregation method for the assessment of connection quality from a network perspective. For this sub-objective, we can state the following research question:

Which aggregation methodology is appropriate to aggregate routes in a route set and to determine the quality of the connection?

The second sub-objective is to determine the perceived connection travel time reliability from a user perspective and how this is affected by route choice. For this sub-objective, we can determine the following research question:

What defines the perceived reliability of the user and how is this influenced by route choice?

The practical application of the theoretical basis in a model provides insight in the aggregation methodology and the practical use when considering measures for the improvement of the connection. The application can be divided in two parts. The first part is the application of the network perspective aggregation method in order to determine the difference between connection quality in the morning peak hour and outside the peak hour and between urban and highway connections. For this, the following research question is stated:

How does the connection quality depend on the time of day and on the type of connection?

The second part is the application of trip travel time distributions for different types of users. A distinction is made between a uninformed, normal and fully informed traveler. Furthermore, the effect of having variable departure times is investigated by assuming a user with a static departure time and a user that has a certain predetermined time interval for departure. For this part, the research question is as follows:

What is the relationship between the type of user and the perceived connection reliability?

In order to answer these research questions an assessment was made of current literature in the field of reliability. Therefrom, an aggregation method is proposed for the network and user perspective. The new aggregation concepts are applied in a model framework, designed for a practical application of the proposed methodology. The model is designed in detail and then applied and tested in a case study in the Amsterdam city region. The results of application and the aggregation methods are discussed and it is concluded whether the model yields the results desired. Lastly, recommendations for improvement of the proposed aggregation methods and the implemented model design are presented, as are directions for further research.

Route aggregation

Network perspective: Connectivity indicator

From a network perspective, the aggregation of a route set or connection between an origin and destination is achieved by the application of an adapted version of the Logsum method. This

provides an assessment of the actual travel times of the routes and the number of alternatives within the route set of the connection. This indicator is referred to as the ‘connectivity indicator’. The connectivity indicator value represents the quality of the connection at the measured time. For comparability between connections, we use the freeflow travel time of the fastest freeflow route in the route set to normalize the value. The input for the connectivity indicator is thus the difference between the actual measures travel times and this reference freeflow travel time.

User perspective: Perceived connection reliability

From a user perspective, the influence of route choice on the perceived travel time reliability of the user is investigated, as the set of routes taken determines the travel time reliability perceived. The travel time reliability can be determined on trip level by ascertaining the travel times of the routes chosen by the user. We can determine that aspects of the trip travel time distribution, such as the reliability, are therefore dependent on route choice. Furthermore, as this type of aggregation of routes still leads to a travel time distribution, the reliability can be determined using (conventional) distribution based performance indicators.

Model design

Purpose of the model

The purpose of the model is to provide insight in the practical use of the proposed aggregation methodology through the application of an exemplary model framework. The results of the designed model applied in a case study can be used to answer the practical application research questions.

In this designed model framework, the methodology is applied on several exemplary issues incorporating recurrent and non-recurrent events. As such, the methodology is applied during a peak hour interval and, as a reference, during an interval outside of the peak hour. The connectivity indicator is applied to determine how the connection quality depends on the time of day and the type of connection (proportion of urban and highway routes). The perceived connection reliability is determined for a uninformed, normal and fully informed traveler. Furthermore, the effect of having variable departure times on perceived connection reliability is investigated by assuming a user with a static departure time and a user that has a certain predetermined time interval for departure.

Model framework

The model design comprises two main parts: the model setup for applicability of the methodology and the application of the methodology itself. The model setup for applicability consists of the processing of data and the generation of a representative objective choice set through route set generation. The application of the methodology requires the determination of the model parameter for the connectivity indicator and the assembly of reference trip travel time

distributions for the determination of perceived reliability. The application of the methodology is done in an exemplary case study.

The algorithmic approach of the model framework is enumerated below:

1. **Establishing link based travel times.** Base data element is a network link. Aggregation of link travel times leads to route travel times. If travel times on route level are a priori present this step and step 2 and 3 are unnecessary.
2. **Route set generation.** Establishing the objective choice for a connection through route set generation. Criteria for route set generation are established in the model design; the actual route set generator is case specific.
3. **Trajectories: from link based travel times to route based travel times.** The application of trajectories determines the actual travel times on route level.
4. **Connectivity indicator.** Determination of the effect of time of day and type of connection on connection quality.
5. **Perceived reliability.** Determination of how the level of information influences the perceived connection reliability. Reference distributions are established which are compared to a distribution corresponding to a fully informed user. Furthermore, the effect of variable departure times is investigated.
6. **Implementation of model framework for multiple *OD*-pairs using a case study.** The application of this model design in a case study.

Model setup

Link/route based travel times and route set generation

In order to ensure that the designed model framework is generally applicable, the type of data should have a large coverage of the network. A model structure based on archived historical data is selected as the datasets are large and cover large quantities of the network and time. However, the data can be incomplete or partially erroneous, which has to be compensated for. In this model structure, whenever data regarding actual measures travel times are missing, the freeflow travel time for that road/time is assumed. This is generally the case for lower level parts of the network, therefore such an assumption is reasonable.

The use of archived data requires a transition from a large set of independent measurements to coherent, linked observations derived from the original data set. In order to combine observations to form a route travel distribution, a virtual user passing over the links in the network is assumed. As this user progresses over distance, time progresses. This so-called trajectory of the user can also be simulated in the dataset, as the original set comprises multiple observations at different times. This trajectory can therefore be considered a form of ‘individualization’ of the general dataset.

In order to find route travel times, it is necessary to identify a route set first. This is achieved by route set generation and the determination of the objective route set, which is the representation of the set of feasible routes as determined by the modeler. As such, it is ideal

to validate the created objective routes by comparing to actual routes taken by travelers to determine the coverage of the route set. This requires floating car data, from which these actual taken routes can be derived.

Connectivity indicator settings

The outcome of the connectivity indicator is dependent on the number of alternatives and the travel time dispersion. The sensitivity of the outcome and how it is influenced by the variables is determined with a model parameter. When adjusting the value of the model parameter, this relative sensitivity can be adjusted, thereby determining the sensitivity to the number of alternatives and travel time dispersion. The model parameter is determined so that the effect of 10 minutes of dispersion has about the same effect as having 8 instead of 2 alternatives. This value is chosen at our discretion and can be adjusted in accordance with other research purposes or opinion.

Establishing trip travel time distributions and performance indicators

Empirical reference travel time distributions are acquired by simulating multiple trips for an uninformed user (always taking the same route, which is assumed to be fastest freeflow route) and a 'normal' user who is familiar with the area (based on a route choice model). These reference distributions are referred to as the 'base route' and the 'route choice model' distributions. The base route is determined to be the fastest freeflow route of the connection. The route choice model is based on the Path Size Logit formulation. The reference distributions are compared with a simulated travel time distribution for a fully informed (and compliant) user, which always takes the fastest route available. This is the 'fastest path' distribution. Furthermore, the possible reliability benefits of having a variable departure time in the peak hour are investigated. The comparison is based on several conventional reliability performance indicators (standard deviation, Buffer time Index), a statistical dispersion indicator (Mean Absolute Deviation) and an aggregated delay indicator.

Case study

To provide insight in the results of the proposed framework, the framework is applied on the urban network of Amsterdam, the Netherlands for a total of 8 OD-pairs. Two time scenarios/intervals are considered for a total of 43 Tuesdays in the years 2012-2013: the morning peak hour interval (7h00AM - 10h00AM) and as a reference the midday interval (12h00PM - 15h00PM). The case study network is based on the model network of Navteq, the Netherlands. Acquired data for the network is derived from the NDW ('Nationale Databank Wegverkeergegevens' or Dutch National Database of Road Traffic Data). This data is linked to the model network from Navteq, thereby making it possible to derive corresponding link data when requested.

For the purpose of the research performed in this thesis, the route set generator has the following properties:

1. The algorithm is Dijkstra based.

2. The algorithm employs Labeling to determine the fastest route, the shortest route and the highest comfort route (highest proportion of highway). These are deterministic.
3. A derived form of the K -shortest Path method is used. Link elimination is performed a single time on the fastest route at the link around 50% of the routes distance.
4. After determining deterministic routes, links are subjected to a stochastic influence that slightly alters the measured travel time. After this deviation, the algorithm determines whether a new route has become the shortest.

This route set generation is performed at every observation, thereby acquiring multiple, variable route sets for a single connection of an OD -pair. The variability of the set is dependent on the state of the network and on the degree of stochastic influence on link level. As the route set is aggregated at every observation, this variability is considered desirable as it increases the chance of a representative coverage. The downside can be considered the computation time, as the process of route generation is now repeated at every observation. This process is illustrated in figure 5-4. The parameters used in the route set generator are dependent on the network for which it is implemented.

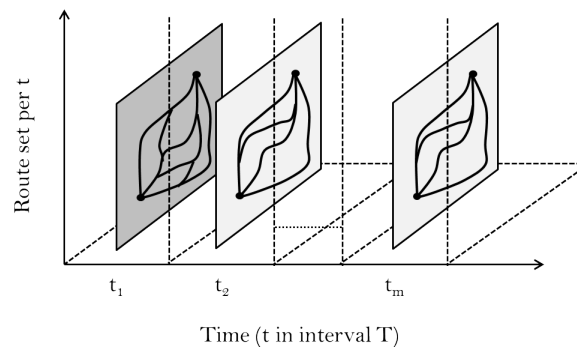


Figure 3: Route sets and variability per interval $t \in T$.

The validation of the coverage of the generated route set generation procedure is conventionally done by comparing with actually observed routes taken by travelers. For this specific case study, no such data is present and therefore the coverage of the route set is based on expert judgment at the discretion of the modeler.

Results of the connectivity indicator

The Logsum measure outcome provides a new insight in the quality differences between connections and shows how the quality deteriorates as the peak hour progresses, while showing stable results for the reference scenario outside of the peak hour. Considering all connections, an average quality degradation of around 14% during the peak hour is observed. It must be noted that standard deviation of the connectivity value over the measured days is significant (occasionally over 30% of the average value) and that although the average shows a steady rise, the standard deviation illustrates that the quality can be significantly different over the days. This is in line with expectation, as not all peak hours are of the same magnitude and

may be influenced by non-recurrent events, such as bad weather or an accident. Outside the peak hour, the differences in quality in freeflow conditions can be observed. As the measure is dependent on the number of alternatives and dispersion, similar quality values may be caused by different ratios between these aspect. From this, it can be determined that the indicator value alone might not be sufficient and that the addition of the ratio between the number of alternatives and dispersion is necessary in order to indicate what the makeup of the indicator value is.

Also, the differences between highway and urban connections are determined. Based on these results one might say that the quality of highway connection is less stable and more sensitive to degradation. However, the coverage of data on the lower network levels and thus on the urban connections, is less than on higher network levels such as highways. The fact that data gaps are compensated for with freeflow travel times may also be the cause of a higher stability of urban connections.

Results of the perceived connection reliability analysis

For the determination of the effect of route choice behavior and information on the perceived connection reliability, the results can be summarized by the following statements:

1. With regard to the base route, it is expected that because it is the fastest freeflow route it should be the fastest under normal condition. We distinguished *OD*-pairs where this was indeed the case and the *OD*-pairs where the base route is rarely the fastest. The last is contradictory to expectation, as no delay is expected and thus freeflow travel times should be observed under normal conditions.
2. The route choice model shows occasional improvements with regard to travel time reliability, but has a persistent higher average and delay. This is in line with expectation as the route choice process is based on more properties except travel time.
3. The fastest path algorithm represents a traveler that is fully informed about what routes are the fastest at a particular time. The results show a persistent improvement when comparing to the reference distributions. With the exception of a single connection where the base route is always the fastest as well, large improvements with regard to reliability and delay can be achieved when fully informing a traveler. Note that the improvement of the average is much smaller compared to the reliability benefits.

For the determination of the effect of having a variable departure time, the results can be summarized by the following statements:

1. Most indicators show a consistent improvement of the distribution for a variable departure time in comparison with a static departure time. This greatly differs between the *OD*-pairs and ranges from 0% to 50%.
2. The Buffer time Index indicator shows great fluctuations, even within the connections. Furthermore, the results are often in conflict with the other performance indicators. In case of one connection, the Buffer time Index was 0 at 7h00AM, thereby making a relative comparison impossible. For the remainder of this analysis, the Buffer time Index is considered with reservations.

3. The improvements are most notable for the highway connections.
4. The improvements are larger for a larger interval around the static departure time. This is in line with expectation since more departure times are considered and thus the chances of having a better option increases.
5. The improvements increase as the peak hour progresses for most *OD*-pairs, meaning that improvements are more notable for 8h30AM and 8h00AM. At 7h00AM, the improvements are much smaller. For other *OD*-pairs, the peak of improvements can be found at 8h00AM, suggesting that the peak hour is not at its maximum at the same time in the observed interval of the day for every connection.

Conclusions and recommendations

The objective of the research has been to give insight in the variability of route sets and travel times in a large network and how they differ depending on the *OD*-pair observed and over time. Therefrom the goal was to determine a method to determine the travel time reliability of an entire connection between an *OD*-pair through the aggregation of routes travel times.

The application of the connectivity indicator as an aggregation methods was determined appropriate. However, the addition of the ratio between the number of alternatives and the dispersion provided insight in the makeup of the value.

The influence of route choice on the perceived travel time was determined to be significant. A high level of information may, in an optimal situation where the traveler is fully compliant, lead to a more optimal use of the connection, thereby reducing travel time and increasing travel time reliability. It can also be concluded that the fastest freeflow route is in case of no information usually a good option. A traveler basing his route choice on other aspects is likely to be affected by this in his experienced travel time reliability. The departure time is, especially in the peak hour, also of influence. It can be concluded that having a variable departure may significantly improve the perceived reliability in relation to a static departure time. This effect is most notable for departure times later in the peak hour.

Recommendations are further improvement of the connectivity indicator by assigning qualitative value to the outcome of the indicator and the inclusion of overlap and dominance. Also the effects of changes in connection layout on the outcome should be evaluated. For the perceived reliability analysis, further investigation into the traveler compliance, the route choice model estimation and the degree of flexibility of the departure time is necessary. Furthermore, the use of a static route set per connection is recommended in order to reduce computation time.

Directions for further research are the application of utility values instead of solely travel time, the investigation into the evening peak hour and the development of a reliability based accessibility index for locations.

Table of Contents

Preface	i
Summary	iii
Definitions	xxi
1 Introduction	1
2 Reliability in literature	7
2-1 Reliability, variability and robustness	7
2-2 Reliability classes	8
2-3 Travel time reliability	9
2-4 Conventional distribution based performance indicators	12
2-5 Summary	16
3 Route aggregation	19
3-1 Distinction between route sets	19
3-2 Network perspective	21
3-2-1 Conventional aggregation methods	22
3-2-2 Indicator based on travel time	25
3-3 User perspective	29
3-4 Summary	30
4 Model design	33
4-1 Purpose and description of the model	33
4-2 Model framework	34
4-2-1 Algorithmic approach	34
4-2-2 Practical limitations	36

4-3	Model setup	36
4-3-1	Data collection and trajectory method	37
4-3-2	Route set generation algorithm	41
4-3-3	Connectivity indicator	43
4-3-4	Perceived connection reliability: base route, route choice model and performance indicators	45
4-4	Summary	51
5	Case study: Amsterdam	53
5-1	Background	53
5-1-1	Case description	53
5-1-2	Thesis relevance in practice	55
5-2	Network specifications	56
5-3	Data and time specifications	56
5-4	Investigated connections	58
5-5	Route set generator	60
5-5-1	Route set generator specifications	61
5-5-2	Model parameter settings	61
5-5-3	Route set evaluation	63
5-6	Route choice model estimation	65
5-7	Implementation of connectivity indicator	67
5-8	Analysis of perceived connection reliability	72
5-8-1	Travel time reliability and implementation of the fastest path algorithm.	72
5-8-2	Variable departure times	82
5-9	Discussion of results	89
6	Conclusions	93
6-1	Theoretical basis	93
6-2	Practical application	94
6-3	Model setup	96
7	Recommendations	97
7-1	Recommendations for current framework	97
7-2	Directions for further research	99
	References	101
	A Route choice model	107
	B Stability of the connectivity indicator	113
	C Sensitivity analysis of arbitrary model parameters	119

List of Figures

1	Exemplary illustration of route aggregation.	iv
2	Illustration of different route choices and how that affects the travel time distribution.	iv
3	Route sets and variability per interval $t \in T$	ix
4	An illustrative representation of the definitions on route level.	xxii
5	An illustrative connection/route set	xxii
1-1	Exemplary illustration of route aggregation.	2
1-2	Illustration of different route choices and how that affects the travel time distribution.	3
1-3	Report structure.	5
2-1	Indicators for travel time reliability (SHRP2, 2012)	15
3-1	Exemplary illustration of two aggregation methods	24
3-2	Relative influence of constant part of the Logsum ($n = 5, \phi = -1$).	26
3-3	Normalized values for the redefined Logsum set against the number of alternatives and the travel time dispersion ($\phi = -1$).	28
3-4	Example of route sets and single route travel time distribution.	30
3-5	Example of route sets and travel time distribution of a combination of routes.	31
4-1	Model framework	35
4-2	Data specification: measurement intervals	40
4-3	Illustration of erroneous sampling of t_{dep}	41
4-4	Normalized values for the redefined Logsum set against the number of alternatives and the travel time dispersion for $\phi = -0.3$	44
4-5	Aggregation options for time interval T	46
5-1	The target area with the ring road A10 and event area highlighted (Google, 2014)	55

5-2	Model network impression	57
5-3	Investigated <i>OD</i> -pairs	60
5-4	Route sets and variability per interval $t \in T$	62
5-5	Example of irrelevant route (illustrated in green)	64
5-6	Dispersion of the route set size	65
5-7	Averaged value of the connectivity indicator set against the departure	68
5-8	Standard deviation of the connectivity indicator value set against the departure	68
5-9	Relative indication of the influence of the number of alternatives on the connectivity indicator	71
5-10	Travel time distributions for <i>OD</i> -index #1	73
5-11	Travel time distributions for <i>OD</i> -index #2	74
5-12	Travel time distributions for <i>OD</i> -index #3	75
5-13	Travel time distributions for <i>OD</i> -index #4	76
5-14	Travel time distributions for <i>OD</i> -index #5	77
5-15	Travel time distributions for <i>OD</i> -index #6	78
5-16	Travel time distributions for <i>OD</i> -index #7	79
5-17	Travel time distributions for <i>OD</i> -index #9	80
5-18	Travel time distributions for <i>OD</i> -index #1 for different departure times	83
5-19	Relative decrease in delay with variable departure times, for 7h00AM, 8h00AM and 8h30AM.	87
A-1	Travel time distribution for several parameter value of β	110
A-2	Mean value of travel time per value of k	111
A-3	Standard deviation of travel time per value of k	111

List of Tables

2-1	Categorization of travel time reliability related literature based on objective. . . .	9
2-2	Values and distinctions for the Value of Reliability from several exemplary studies in €/h..	11
3-1	Route choice sets and included alternatives (from large to small).	20
4-1	Data collection properties (based on Lomax et al. (2003))	37
4-2	Performance indicators and the criteria. Y: Yes, the indicator complies with the criterion, N: No, the indicator does not comply with the criterion. Based on Pu (2011); Wesseling (2013).	50
5-1	Network properties	56
5-2	Link properties	56
5-3	Case specific periods of time of measuring	59
5-4	Links included in stochastic simulation depending on the value of ζ_{thres}	62
5-5	Overview of route set generation parameters and corresponding values	63
5-6	Parameter values for route choice modeling	66
5-7	Parameter values for route choice modeling	66
5-8	connectivity values for 7h00AM and 10h00AM and the relative change	69
5-9	connectivity values for 12h00PM and 15h00PM and the relative change	69
5-10	Performance indicator values relative to the base route values for <i>OD</i> -pair #1 between 7h00AM and 10h00AM	73
5-11	Performance indicator values relative to the base route values for <i>OD</i> -pair #1 between 12h00PM and 15h00PM	73
5-12	Performance indicator values relative to the base route values for <i>OD</i> -pair #2 between 7h00AM and 10h00AM	74
5-13	Performance indicator values relative to the base route values for <i>OD</i> -pair #2 between 12h00PM and 15h00PM	74
5-14	Performance indicator values relative to the base route values for <i>OD</i> -pair #3 between 7h00AM and 10h00AM	75

5-15	Performance indicator values relative to the base route values for <i>OD</i> -pair #3 between 12h00PM and 15h00PM	76
5-16	Performance indicator values relative to the base route values for <i>OD</i> -pair #4 between 7h00AM and 10h00AM	77
5-17	Performance indicator values relative to the base route values for <i>OD</i> -pair #4 between 12h00PM and 15h00PM	77
5-18	Performance indicator values relative to the base route values for <i>OD</i> -pair #5 between 7h00AM and 10h00AM	78
5-19	Performance indicator values relative to the base route values for <i>OD</i> -pair #5 between 12h00PM and 15h00PM	78
5-20	Performance indicator values relative to the base route values for <i>OD</i> -pair #6 between 7h00AM and 10h00AM	79
5-21	Performance indicator values relative to the base route values for <i>OD</i> -pair #6 between 12h00PM and 15h00PM	79
5-22	Performance indicator values relative to the base route values for <i>OD</i> -pair #7 between 7h00AM and 10h00AM	80
5-23	Performance indicator values relative to the base route values for <i>OD</i> -pair #7 between 12h00PM and 15h00PM	80
5-24	Performance indicator values relative to the base route values for <i>OD</i> -pair #9 between 7h00AM and 10h00AM	81
5-25	Performance indicator values relative to the base route values for <i>OD</i> -pair #9 between 12h00PM and 15h00PM	81
5-26	Relative performance of the variable departure times compared to the corresponding static travel times for <i>OD</i> -pair #1	84
5-27	Relative performance of the variable departure times compared to the corresponding static travel times for <i>OD</i> -pair #2	84
5-28	Relative performance of the variable departure times compared to the corresponding static travel times for <i>OD</i> -pair #3	84
5-29	Relative performance of the variable departure times compared to the corresponding static travel times for <i>OD</i> -pair #4	84
5-30	Relative performance of the variable departure times compared to the corresponding static travel times for <i>OD</i> -pair #5	85
5-31	Relative performance of the variable departure times compared to the corresponding static travel times for <i>OD</i> -pair #6	85
5-32	Relative performance of the variable departure times compared to the corresponding static travel times for <i>OD</i> -pair #7	85
5-33	Relative performance of the variable departure times compared to the corresponding static travel times for <i>OD</i> -pair #9	85
A-1	Parameter values for route choice modeling.	107
C-1	Relative changes of model outcome between 7h00PM and 10h00PM for $\phi = -0.27$	119
C-2	Relative changes of model outcome between 7h00PM and 10h00PM for $\phi = -0.33$	120
C-3	Relative changes of model outcome between 12h00PM and 15h00PM for $\phi = -0.27$	120
C-4	Relative changes of model outcome between 12h00PM and 15h00PM for $\phi = -0.33$	120
C-5	Links included in stochastic simulation depending on the value of ζ_{thres}	122
C-6	Relative changes of model outcome between 7h00PM and 10h00PM for $\zeta_{thres} = 30$ km/h.	122

C-7	Relative changes of model outcome between 7h00PM and 10h00PM for $\zeta_{thres} = 70$ km/h.	123
C-8	Relative changes of model outcome between 12h00PM and 15h00PM for $\zeta_{thres} = 30$ km/h.	123
C-9	Relative changes of model outcome between 12h00PM and 15h00PM for $\zeta_{thres} = 70$ km/h.	123
C-10	Relative changes of model outcome between 7h00PM and 10h00PM for $\zeta_{var} = 0.315$	124
C-11	Relative changes of model outcome between 7h00PM and 10h00PM for $\zeta_{var} = 0.385$	124
C-12	Relative changes of model outcome between 12h00PM and 15h00PM for $\zeta_{var} = 0.315$	125
C-13	Relative changes of model outcome between 12h00PM and 15h00PM for $\zeta_{var} = 0.385$	125
C-14	Relative changes of model outcome between 7h00PM and 10h00PM for $x = 45$	125
C-15	Relative changes of model outcome between 7h00PM and 10h00PM for $x = 55$	126
C-16	Relative changes of model outcome between 12h00PM and 15h00PM for $x = 45$	126
C-17	Relative changes of model outcome between 12h00PM and 15h00PM for $x = 55$	126

Definitions

Theoretical definitions

This section gives a short explanation of frequently used terms in this thesis.

OD-pair: A pair of locations consisting of an origin O and destination D .

Route: Set of connecting roads between a predefined origin and destination, forming a part of the connection for that OD -pair.

Path: Essentially the same as a route. A path can be considered a single unit for a route and is used in mathematical notation.

Trip: A single one-way movement between an OD -pair, of which the exact route/path taken can be undefined.

Connection: Represents the potential of travel between an OD -pair and consists of all the options of travel to do so. In this thesis, we only consider travel options by road.

Connectivity: A quantitative representation of the measure of potential of travel between and OD -pair.

Model element definitions

This section explains the terminology used in regard to network elements. Note that the specifications of the mentioned elements are dependent on the model network implemented.

Node: Specific location or point in the network. Represents the intersection of roads or points where the homogeneous specifications (e.g. maximum speed, number of lanes, etc.) of the road change. Connection point of two links.

Link: Connecting element. Network element that represents a part of a road or set of roads with homogeneous specifications and connect two nodes in the network.

Trajectory: A construct representing a virtual movement over the network, thereby taking into account the time passed during the movement. This construct can be expressed in a space-time diagram.

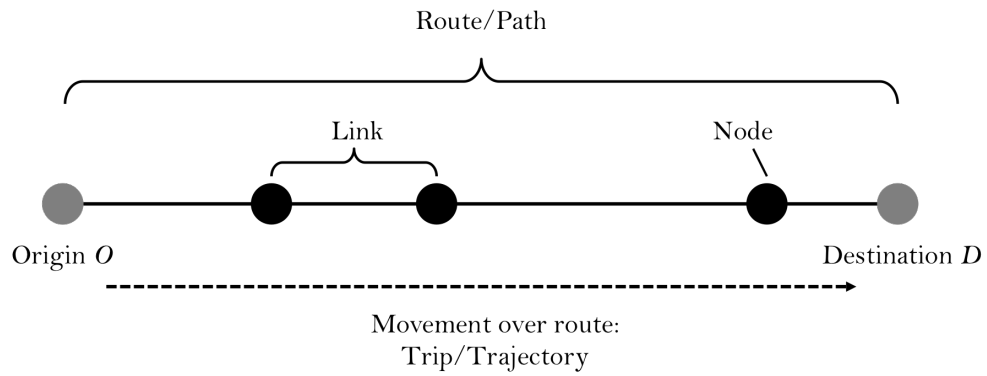


Figure 4: An illustrative representation of the definitions on route level.

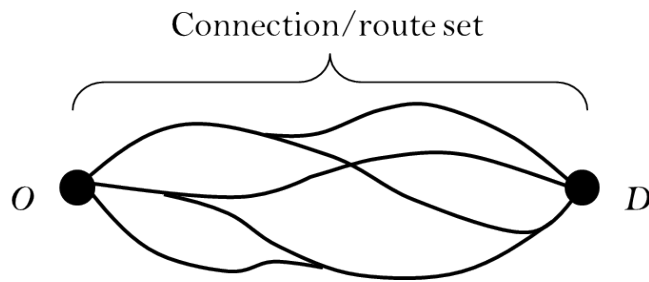


Figure 5: An illustrative connection/route set

Chapter 1

Introduction

The majority of personal and business transport is by road. Road networks in and around urban environments are therefore often dense and extensively used. As such, proper functioning of the road network in these areas is of critical importance as many people are depending on it. However, it is not evident how the functioning of a network can be assessed and analyzed.

When analyzing the functioning of a network, many aspects can be considered of importance. Conventionally, the analysis of network performance is based on the estimation and evaluation of average conditions (speed, travel times or generalized costs) for a given time period for a specific network element (e.g. road segments and routes). However, Hellinga (2010) stated that by averaging these terms the influence of the variability of conditions of the network is not reflected in the outcome of the analysis and thus missing a critical aspect in the appreciation of the network. An averaged indicator does not reflect on the variation of that indicator. A reliable transportation system should maintain an acceptable operational standard in spite of deterioration of certain (parts of) roads in the network. Chen et al. (2002) pointed out that the stability (or the variability of the performance) of the network greatly reflects on the quality of service the network would normally provide. Besides the network perspective, the effect of variation of conditions directly affects the user and how he uses the network. Consistent and significant variation of network conditions may lead to unexpected costs to the user, either in time or money. As such, the user is unable to rely on the network and may change his travel behavior.

Despite all this, the inclusion of variability of conditions as a possible influence on travel behavior is a relatively new approach (Hellinga, 2010). The most obvious and easily interpreted indicator is travel time. When making a trip through the network, the travel time of that trip is dependent on many conditions. These conditions can be the amount of other travelers,

the capacity of the taken roads or something trivial as the weather. Some of these conditions vary over time, thereby leading to variations in travel time for that trip depending on when the trip is made. The variation of travel time and how it affects users and the network is a relatively new research subject in transport and mobility, leading to the fact that, regarding assessment methodology, a general consensus has yet to be reached (Hellings, 2010).

If we consider a trip on a road network, we can identify an origin (point of departure) and destination for that trip. The origin and destination (or OD -pair) are connected by a road network, or it can be said that there is a connection between O (origin) and D (destination). In case of an urban network, the network is often elaborate, providing multiple route options for single connection to take.

Conventionally, we can indicate travel time reliability of separate routes, thereby ascertaining a corresponding travel time distribution from which the travel time reliability can be derived. Although this process can be done for all routes in the route set of the connection separately, no specific indication for the quality of the route set can be derived from this with current methodology described in literature. From a network perspective, ascertaining a measure to determine the aggregate of routes in the route set and their collective properties is desirable in order to be able to assess the quality of the connection. An illustration is presented in figure 1-1.

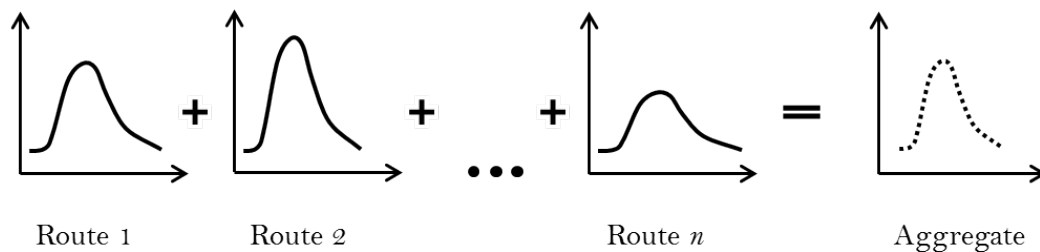


Figure 1-1: Exemplary illustration of route aggregation.

From a user perspective, route travel time reliability can only be perceived after taking the route a number of times and thereby experiencing the variations in travel time. As such, users that are unfamiliar with the connection between the origin and destination are thus also unfamiliar with the optional routes and their specifics, such as travel time and travel time reliability. They may have no initial perception of the reliability of the travel time of the routes in the route set and therefore their travel behavior may be different from a user who is familiar with the connection. For example, an uninformed user may always use the same route for his trip, while a fully informed user may alter his chosen route according to the state of the network. As such, it leaves the question if and in what degree the first user will experience travel time reliability of his trip differently compared to the second user. This example is illustrated in figure 1-2.

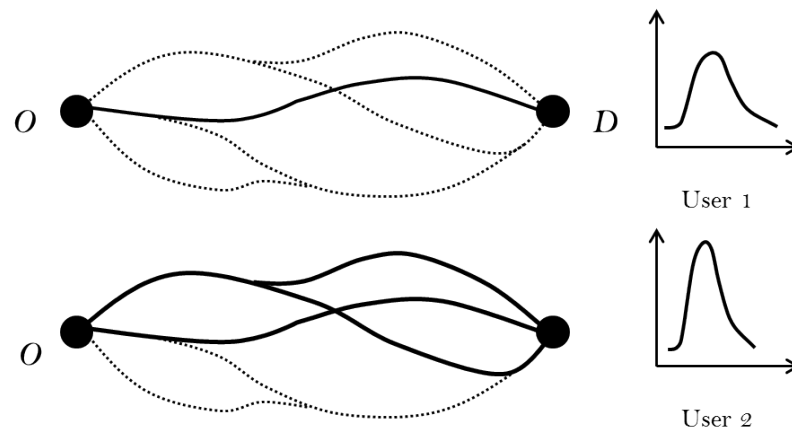


Figure 1-2: Illustration of different route choices and how that affects the travel time distribution.

In short, we can determine the travel time reliability of separate routes and the influence on route choice, but there is no method yet to determine how route choice determines the perceived reliability of the connection between the OD -pair.

The objective of the research reported is to give insight in the assessment of a set of routes in a connection, thereby aggregating routes and their collective properties. The main contribution of this thesis is divided into in a theoretical basis and a practical application. The theoretical basis comprises two parts. The first is to select and test an aggregation method for the assessment of connection quality from a network perspective. For this sub-objective, we can state the following research question:

Which aggregation methodology is appropriate to aggregate routes in a route set and to determine the quality of the connection?

The second sub-objective is to determine the perceived connection travel time reliability from a user perspective and how this is affected by route choice. For this sub-objective, we can determine the following research question:

What defines the perceived reliability of the user and how is this influenced by route choice?

The practical application of the theoretical basis in a model provides insight in the aggregation methodology and the practical use when considering measures for the improvement of the connection. The application can be divided in two parts. The first part is the application of the network perspective aggregation method in order to determine the difference between connection quality in the morning peak hour and outside the peak hour and between urban and highway connections. For this, the following research question is stated:

How does the connection quality depend on the time of day and on the type of connection?

The second part is the application of trip travel time distributions for different types of users. A distinction is made between a uninformed, normal and fully informed traveler. Furthermore,

the effect of having variable departure times is investigated by assuming a user with a static departure time and a user that has a certain predetermined time interval for departure. For this part, the research question is as follows:

What is the relationship between the type of user and the perceived connection reliability?

In order to answer these research questions we make an assessment of current literature in the field of reliability in Chapter 2. Therefrom, an aggregation method is proposed for the network and user perspective in Chapter 3. The new aggregation concepts are applied in a model framework, designed for a practical application of the proposed methodology. The model is designed in detail in Chapter 4 and then applied and tested in a case study in the Amsterdam city region in Chapter 5. The results of application and the aggregation methods are discussed and it is concluded whether the model yields the results desired in Chapter 6. Lastly, recommendations for improvement of the proposed aggregation methods and the implemented model design are presented in Chapter 7, as are directions for further research. This report structure is also represented in figure 1-3.

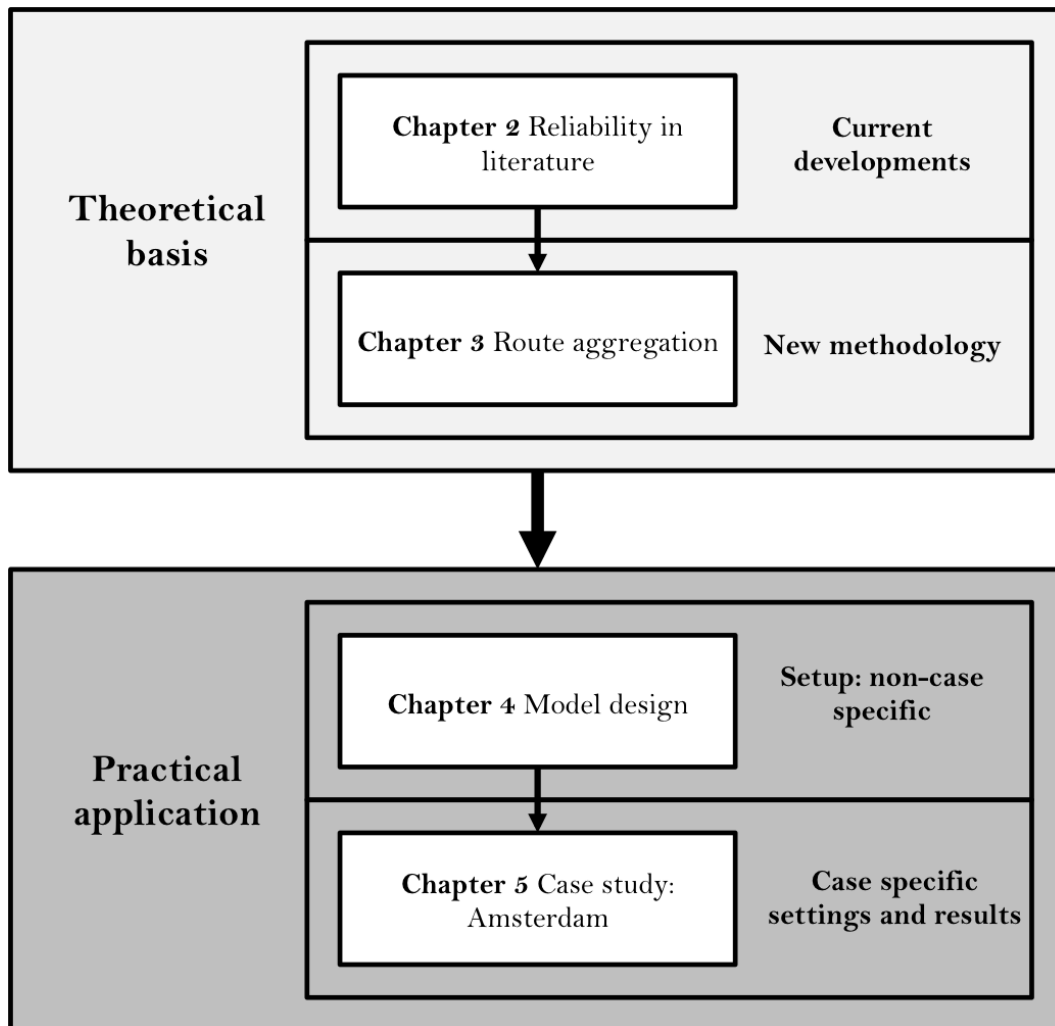


Figure 1-3: Report structure.

Reliability in literature

This chapter elaborates on the definition of reliability and on different classes of reliability. Section 2-1 explains how the definitions of reliability, variability and robustness relate to each other and section 2-2 defines the different reliability classes used in current literature. Section 2-3 lists and categorizes current literature in travel time reliability and its shortcomings regarding the evaluation of a connection. Section 2-4 elaborates on multiple performance indicators for travel time reliability based on travel time distributions. Section 2-5 presents a summary of the findings in this chapter.

2-1 Reliability, variability and robustness

Variability of the network operational conditions can be considered a system performance indicator from an operator or traffic facility perspective. It relates more to the concerns of network operating agencies as users experience variability subjectively (Lomax et al., 2003). However, considering the network performance, one may identify two other closely related system performance indicators: *reliability*, and *robustness*. Lomax et al. (2003) explained that the definition of variability takes the ‘objective’ operators perspective, while reliability is more commonly used to ‘subjectively’ reference to the user experience of the level of consistency provided. Reliability can be defined as the probability of a road network performing adequately at the proposed service level intended for a period of time under the operating conditions encountered (Billington and Allan, 1992; Wakabayashi and Iida, 1992). In a way similar to variability, robustness can be considered a performance indicator of the system as well. Immers et al. (2004) defines robustness as the ability of traffic networks to cope with exceptional changes in the demand and supply pattern. Immers et al. (2004) furthermore state

that, in relation to reliability, robustness is a characteristic of the network, while reliability is a user-oriented quality.

Furthermore, Snelder and Tavasszy (2010) identified a few other distinctions between robustness and reliability. First, concerning reliability, the emphasis lies on regular occurring disturbances or recurrent events, whereas with robustness this lies on unexpected, large-impact disturbances or non-recurrent events (e.g. incidents, extreme natural occurrence). Second, reliability is determined over a longer period of time, while robustness is considered in the time interval of the disturbance. Third, reliability is focused on the chance of occurrence of a specific disturbance, whereas robustness focuses on the effect of the disturbance (for a more elaborate explanation, we refer to Snelder and Tavasszy (2010)).

In this thesis, longer periods of time are analyzed in order to capture the effects of recurrent and non-recurrent events on the quality of a connection. Based on this paragraph, the system performance indicators variability, for the network perspective, and reliability, for the user perspective, are the most adequate.

2-2 Reliability classes

Clark and Watling (2005) identified five classes of reliability.¹² The first class is *connectivity reliability*, whereby each link of the network is assumed to have an independent, probabilistic and binary mode of operation. This binary aspect may refer to the availability of a link in the network (by being either closed or open) or may reflect on a more subjective definition of the successful function of a link. The objective of this method is to determine the probability that a particular path or *OD* movement is connected in one or more ways or, more generally put, will function as desired. Iida and Wakabayashi (1989) originally designed this method for extreme, non-recurrent circumstances, such as (natural) disasters or extreme incidents. However, the binary aspect of this method makes it unsuitable for the evaluation of recurrent events (e.g. peak-hour congestion) (Li, 2009; Ng et al., 2011).

The second class is *capacity reliability*, where reliability is assessed in the context of variation in link capacities (for more explanation, we refer to Chen et al. (2000, 2002); Siu and Lo (2008)).

The third class comprises *behavioral reliability*, whereby an effect on mean network performance is presumed to arise from the modified, mean behavior of drivers in their attitude to the unpredictable variation of the network performance and/or the risks perceived. The issue is then how to represent the impact of that variation on the route choice pattern or on other responses such as departure time choice.

¹The order is not a display of appreciation.

²See Clark and Watling (2005) for additional accompanying references.

The fourth class is *potential reliability*. Here the aim is to identify potential weak points or problems in the network and their effect(s), for example methods that determine network vulnerability. Snelder et al. (2012) designed a framework for robustness analysis and Knoop et al. (2012) attempted to identify vulnerable links in the network.

The fifth and last class assesses *travel time reliability*. Coifman (2002) indicated that link travel time (and thus route travel time derived therefrom) is most informative to the user of the network (compared with capacity, occupancy, flow, etc.) and as a result thereof the reliability of travel time is regarded as the most expressive and easily communicated of the reliability classes. The research reported in this thesis belongs to the travel time reliability class and this class is therefore elaborated more in detail.

2-3 Travel time reliability

The objectives of current literature in travel time reliability can be mutually distinguished and listed in four categories, determined at our own discretion, represented in table 2-1.³

Category	Explanatory	Literature
Descriptive	Descriptive analysis of reliability indicators or measures.	Lomax et al. (2003); Van Lint et al. (2008); Pu (2011); Palsdottir (2011).
Behavioral	Effects of reliability on travel behavior (route choice).	Papinski et al. (2009); Bogers et al. (2005); Avineri and Prashker (2005); De Palma and Picard (2005); Liu et al. (2004); Xu et al. (2011).
Valuation	Determining the value of (un)reliability from a certain perspective.	(De Jong et al., 2009; Warffemius, 2002; Li et al., 2009; Eliasson, 2004; Fosgerau et al., 2008; Brownstone and Small, 2005; Lam and Small, 2001; Bates et al., 2001).
Forecasting	Forecasting reliability on a network depending on demand and network properties.	Bell et al. (1999); Du and Nicholson (1996); Clark and Watling (2005); Ng et al. (2011); Wesseling (2013).

Table 2-1: Categorization of travel time reliability related literature based on objective.

The first category consists of studies performing descriptive analyses of travel time reliability, for example evaluating performance indicators (Lomax et al., 2003; Van Lint et al., 2008; Pu, 2011). Lomax et al. (2003) generally discussed methods to define travel time reliability, using performance indicators. Van Lint et al. (2008) expanded on this by adding a few indicators. Pu (2011) analytically compared the performance indicators in order to determine which is the most ‘representative’ for travel time reliability. Palsdottir (2011) determined the effect of employed traffic measures on travel time reliability, whereas measures are investigated on a route scale.

The second category focuses on the causal relationship between travel time reliability and

³Note that the mentioned studies are examples and therefore by definition non-exhaustive.

travel behavior (Bogers et al., 2005; De Palma and Picard, 2005; Xu et al., 2011; Liu et al., 2004). Fluctuations in travel time affect the user's route choice. Papinski et al. (2009) found that of all route choice attributes, reliability is valued highest after safety. Bogers et al. (2005) determined that routes with a wider travel time distribution are more undesirable than routes that have a lower general mean, but have occasional extreme travel times (positive skew), indicating that uncertainty is a significant influence on route choice besides the average travel time. Avineri and Prashker (2005) stated that the influence of travel time reliability on route choice becomes less as the variance increases. In addition, they found in some cases that increased variability of less attractive routes can increase its perceived attractiveness, since perception of travel time is biased. De Palma and Picard (2005) tried to capture travel time reliability effect by using Expected Utility Theory (EUT), based on surveys. Liu et al. (2004) also used utility theory, but instead based on real-time loop detector data. Xu et al. (2011), however, pointed out that utility theory based methods are based on the assumption that travelers have perfect knowledge about the travel scenario and are completely rational when making route choice decisions. In reality, travel behavior is influenced by personality, psychological state, risk preference, spatial surroundings, among others. Basing on Bleichrodt et al. (2007), they propose using Cumulative Prospect Theory (CPT) based on survey data. All the same, when accounting for en route decision making, both EUT and CPT fall short as they do not depend on the traveler's knowledge. Yet Papinski et al. (2009) observed that 20% of travelers change their pre-trip chosen route while on their way and thus this can be considered an important aspect of route choice. Avineri and Prashker (2005) proposed the use of learning models that incorporate psychological elements, traveler learning capability and en route decision making, but note that it remains a trade-off between the "elegance and simplicity" of utility theory and the accuracy of learning models.

The third category embodies literature determining the valuation of travel time reliability (De Jong et al., 2009; Warffemius, 2002; Li et al., 2009; Eliasson, 2004; Fosgerau et al., 2008; Brownstone and Small, 2005; Lam and Small, 2001; Bates et al., 2001). This category is in a way similar to the second category, as the value of travel time reliability influences travel behavior. Yet the emphasis in this category lies on the value, not on the specific effect on travel behavior. In this particular field there has been extensive research, although a general consensus has yet to be reached (also see table 2-2⁴). A possible cause for this are the widely diversified approaches the different studies employ. Peer et al. (2012) endorses this suggestion by noting the difference in outcome between urban road network studies and highway focused studies. Eliasson (2004) distinguished by separating different moments for the time of day and stated that reliability, unexpected delays and queue driving should be monetized separately as they are, by definition, different. Lam and Small (2001) distinguishes by gender. Table

⁴Note that the values have been expressed in Euros and rounded to integers. Changes in inflation and values of monetary units have not been taken into account. For original values we refer to the corresponding study.

2-2 shows significant variation in appreciation of travel time reliability. For a comparison of methods and results of a number of studies in this category, we refer to Li et al. (2009).

Study	Value of Reliability (€/h)	Country	Comment
Lam and Small (2001)	9 & 22	USA	Male & Female
Bates et al. (2001)	9	Great Britain	-
Warffemius (2002)	6	Netherlands	-
Eliasson (2004)	4 & 2	Sweden	Averaged over traffic states. Morning & Afternoon
Brownstone and Small (2005)	5	USA	-
Fosgerau et al. (2008)	4 & 3	Denmark	8 AM & 10 AM

Table 2-2: Values and distinctions for the Value of Reliability from several exemplary studies in €/h..

The fourth category attempts to forecast travel time reliability (Du and Nicholson, 1996; Bell et al., 1999; Clark and Watling, 2005; Ng et al., 2011; Wesseling, 2013). These studies employ a continuous probabilistic treatment of link travel times and subsequently path and route travel times. Bell et al. (1999) and Du and Nicholson (1996) all assumed the demand to be stochastic and proposed a simulation-based method for examining the impact of variability in *OD* demand levels, whereby an *OD* demand matrix is sampled and an equilibrium assignment (the assignment of flow to the network) performed for each sampled demand. Bell et al. (1999) added to this a sensitivity analysis of the equilibrium to reduce model computation time. Du and Nicholson (1996) do this as well, but focus on the multi-modal aspect. Also using a stochastic demand, Clark and Watling (2005) provided a means for identifying sensitive or vulnerable links and for examining the impact of changes to link capacities on network reliability. Ng et al. (2011) presented a method to assess travel time reliability that is distribution-free in the sense that the methodology only requires that the first N moments (where N is a user-specified positive integer) of the travel time to be known and that the travel times reside in a set of bounded and known intervals. Wesseling (2013) attempts to forecast and simulate travel time reliability on a door-to-door level using marginal modeling basing on Corthout (2012) and Corthout et al. (2014).

The categorization shows a large variety in current literature research subjects. However, shortcomings are to be found when reliability is to be determined on the scale of a connection. When a trip is made between an origin and destination, the travel time reliability of that trip is dependent on a set of possible routes instead of just a single route as a connection usually consists of multiple route options. Determination of the travel time reliability performance of this trip can therefore not be determined by evaluating a single route only. The aspect of having alternatives is not taken into account in current descriptive literature for the evaluation of the travel time reliability performance. The assessment of the connection can

be evaluated from two perspectives: the network perspective and the user perspective. The network perspective considers all feasible route options between the origin and destination and the aggregate of their aspects. Current literature shows measures to evaluate and simulate travel time reliability on an individual route, but no methodology for the assessment of the aggregate of routes could be found. From a user perspective, a similar shortcoming in literature could be determined. The effects of route travel time reliability on route choice can be determined (second and third category), but no indication is given of how route choice affects the travel time reliability the user perceives when making this trip multiple times. This perceived reliability can be derived from the travel time distribution for the trip (which may or may not be using a set of routes instead of just one). The evaluation of this travel time distribution can be done similar to the evaluation of the distribution of a route.

2-4 Conventional distribution based performance indicators

Current research already states a number of techniques to indicate travel time reliability based on travel time distributions.⁵ Note that these indicators evaluate travel time distributions independent of network elements (links, routes, etc.) and consequently are therefore also adequate for the evaluation of a trip travel time distribution.

We can observe the overlap between variability and reliability. Variability is the objective (statistic) aspect of the distribution, while reliability is a subjective appreciation of the distribution. Some methods use the variability to judge the distribution, while other methods use probability and relativity. The methods can be divided into five categories (Lomax et al., 2003; Van Lint et al., 2008).⁶ We assume a random, sample based travel time distribution S , where τ_i a travel time observation.

Statistical range methods

Standard deviation (SD, σ) or semi-standard deviation of travel time on a given time of day (TOD), day of the week (DOW) period or the coefficient of variation (COV, c_v) or relative standard deviation (also known as percent variation) ($\%RSD$, c_v) on a given TOD, DOW period (Bates et al., 2001; Lomax et al., 2003). For mathematical expressions see equations (2-1) respectively.

⁵In order to avoid confusion, note that travel time reliability performance indicators are a subdivision of the system performance indicator 'reliability'.

⁶The terminology and notation of these methods may differ between studies, we mostly follow that of Van Lint et al. (2008).

$$\mu = \frac{\sum_i \tau_i}{n} \quad (2-1a)$$

$$\sigma = \sqrt{\frac{1}{n-1} \sum_n (\tau_i - \mu)^2} \quad (2-1b)$$

$$c_v = \frac{\sigma}{\mu} \quad (2-1c)$$

$$\sigma_{rel} = \frac{\sigma}{\mu} \times 100\% = c_v \times 100\% \quad (2-1d)$$

where μ is the mean travel time and n the number of observations.

Buffer time indexes

The Buffer time index (BI) indicates the percentage extra travel time a user should leave earlier than on average, to still arrive on time (in 90% of the cases) on a given TOD, DOW period. This is specifically interesting when considering the influence of travel time reliability on departure time in order to arrive at a preferred time (planning time) (Lomax et al., 2003). This can be based on the mean of the distribution (2-2).

$$BI = \frac{\tau_{90\%} - \mu}{\mu} \quad (2-2)$$

or it can be based on the median (2-3).

$$BI = \frac{\tau_{90\%} - \tau_{50\%}}{\tau_{50\%}} \quad (2-3)$$

The Planning Time index is the ratio of the 95th percentile travel time over free flow travel time. It expresses the extra time a user should budget in addition to free-flow travel time to arrive on time 95% of the time (Pu, 2011).

$$PI = \frac{\tau_{95\%}}{\tau_{ff}} \quad \tau_{ff} = \quad (2-4)$$

where τ_{ff} is the free flow travel time.

Tardy trip measures

The Misery index (MI) calculates the relative distance between the mean travel time of the 20% worst trips and the mean travel time of all users on a given TOD, DOW period (Lomax et al., 2003).

$$MI = \frac{\mu|_{\tau_i > \tau_{80\%}} - \mu}{\mu} \quad (2-5)$$

Probabilistic measures

These measures calculate the probability that travel times occur larger than α times some predefined travel time threshold. In this case a parametrized multiplication of the median travel time as the threshold on a given TOD, DOW period is illustrated (Bell, 1999).

$$PR(\alpha) = P(\tau_i \geq \alpha \times \tau_{50\%}) \quad \text{where e.g. } \alpha = 1.2 \quad (2-6)$$

Skew-width indicator

Based on empirical analysis, Van Lint et al. (2008) proposed additional performance indicators: the skewness and width of the distribution. As the state of traffic changes (e.g. from free-flow to congestion), so does the nature of the distribution. Generally, the width of a distribution is statistically expressed as the SD or the COV and the (sample) skewness G is mathematically expressed as a function of the mean and SD in (2-7).⁷

$$G = \frac{n}{(n-1)(n-2)} \sum_n \left(\frac{\tau_i - \mu}{\sigma} \right)^3 \quad (2-7)$$

As this function depends on the statistical values for the mean and SD, the result is sensitive to outliers in the dataset, compromising the outcome (Van Lint et al., 2008). It is therefore that Van Lint et al. (2008) propose to express the width and skewness as “simple metrics”, based on percentile intervals of the distribution. As both are indicative for the travel time reliability, Van Lint et al. (2008) proposed an indicator that combines both aspects: the skew-width indicator.

Width of the distribution can be determined with the distance between the 90th and the 10th percentile divided by the median. The skewness of the distribution is calculated by the ratio of the distance between the 90th percentile and the median and the distance between the median and the 10th percentile, values larger than 1 are for positively skewed distributions. Mathematically, they are presented in equations (2-8).

⁷The expression used in Van Lint et al. (2008). This is the adjusted Fisher-Pearson standardized moment coefficient, used in conventional statistical software.

$$\lambda_{var} = \frac{\tau_{90\%} - \tau_{10\%}}{\tau_{50\%}} \quad \text{where} \quad \tau_{10\%} < \tau_{50\%} < \tau_{90\%} \quad (2-8a)$$

$$\lambda_{skew} = \frac{\tau_{90\%} - \tau_{50\%}}{\tau_{50\%} - \tau_{10\%}} \quad (2-8b)$$

Derived from these indicators, Van Lint et al. (2008) propose the skew-width indicator (2-9), which is conditional depending on the value of λ_{skew} , therefore taking into account the transient periods between congested and non-congested traffic states (for motivation and elaboration we refer to Van Lint et al. (2008)).

$$SW = \begin{cases} \frac{\lambda_{var} \ln \lambda_{skew}}{L_r} & \text{if } \lambda_{skew} > 1 \\ \frac{\lambda_{var}}{L_r} & \text{otherwise} \end{cases} \quad (2-9)$$

These methods can be illustrated when considering a random travel time distribution S (see figure 2-1).⁸

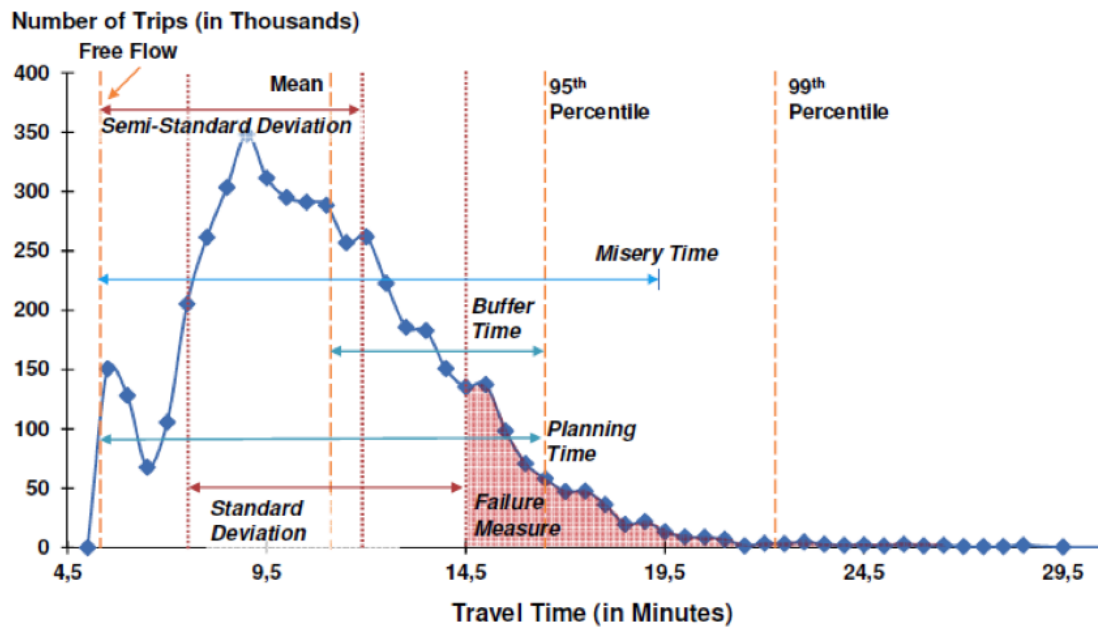


Figure 2-1: Indicators for travel time reliability (SHRP2, 2012)

The general consensus of different (descriptive) literature is that despite the number of different measurement techniques there is not a specific measure method that is ‘the most reliable’. The reliability of the measure greatly depends on the objective of the research and the quan-

⁸The skew-width indicator is not illustrated in the figure.

titative criteria that are chosen. As measurements of travel time usually include extreme values (due to non-recurring events), Van Lint et al. (2008) recommended that the skew of the distribution of the travel time is always included in order to capture the effects caused by these extreme values. In addition, statistical based measures are more sensitive to these extreme outliers, which may influence the results. On the other hand, statistical indicators are currently the only that can be expressed monetary, thereby being critical when performing a cost-benefit analysis. Furthermore, Van Lint et al. (2008) stated that the use of parametrized measures, or specifically the probability based measures, are greatly dependent on the expert judgment that determines these parameter values. A change in parameter can significantly influence the reliability results. Pu (2011) also analyzed the performance indicators, with the exception of the relatively new skew-width indicator and concluded the coefficient of variation (COV) to be the best 'proxy' of or representation for the other measures. Lomax et al. (2003) recommends the more comprehensible relative standard deviation (%RST) or percent variation, basically a percentage based COV, as it is more easily communicated with the public. Both indicators are however based on the mean and standard deviation and therefore sensitive to outliers.

2-5 Summary

In this chapter, first a distinction is made between different system performance indicators of which reliability and variability are concluded to be the most adequate with respect to the objective of this thesis. Second, we can distinguish between several reliability classes. These classes embody different measures for the determination of the reliability of network elements and serve different purposes. This thesis belongs to the travel time reliability assessment class, as it investigates both recurrent and non-recurrent events and the user perspective is included.

Furthermore, within the class of travel of travel time reliability, current literature is subdivided in four categories at our discretion, depending on the research subject. The categorization shows a large variety in current literature research subjects. However, there are shortcomings to found when reliability is to be determined on the scale of a connection. With respect to the objective of this thesis, it can be determined that no literature was found assessing travel time reliability on the scale of connection from both a network and a user perspective. The network perspective considers all feasible route options between the origin and destination and the aggregate of their aspects. Current literature shows measures to evaluate and simulate travel time reliability on an individual route, but no methodology for the assessment of the aggregate of routes could be found. From a user perspective, the effects of route travel time reliability on route choice can be determined (second and third category), but no indication is given of how route choice affects the travel time reliability the user perceives when making

this trip multiple times. Depending on the user and the route set used, a trip travel time distribution can be assembled. Although the assembly methodology of this distribution is not yet investigated, the distribution can be evaluated in a way similar to that of a route with conventional distribution based performance indicators.

Chapter 3

Route aggregation

In this chapter, a new methodology is proposed for the aggregation of routes in a route set of a connection for the network and user perspective. Section 3-1 discusses different definitions of route sets and the set required for aggregation. Section 3-2 proposes a measure for the aggregation of a route set and corresponding travel times to a single representative indicator, referred to as the ‘connectivity indicator’. Section 3-3 discusses the assembly of trip travel time distributions from route travel time distributions and how this can be used to determine perceived reliability. Finally, section 3-4 presents a summary of the conclusions drawn in this chapter.

3-1 Distinction between route sets

The aggregation of route travel times requires a route set per connection. Ideally, the route set of a connection is a priori determined, with all routes taken by users on the connection and no redundant routes included in the route set. In reality, usually the best approximation of this ideal route set is achieved by a route set generation procedure. This section provides theoretical insight in the route sets and route set generation and what is the best approximation of the ideal route set applicable for aggregation.

In route set generation, we can distinguish between the user and the modeler. Let us define the total set of possible alternatives as the *universal set* \mathcal{U} (Fiorenzo-Catalano, 2007).

The user is aware of a certain subset of the universal set of alternatives, but only considers a part in his actual choice. The alternatives that is known to user are referred to as the

subjective choice set \mathcal{N} and the alternatives that are actually considered in the choice process are the *consideration set* \mathcal{N}_C (Fiorenzo-Catalano, 2007). Both sets are user specific.

$$\mathcal{N}, \mathcal{N}_C \subseteq \mathcal{U} \quad (3-1)$$

$$\mathcal{N} \subseteq \mathcal{N}_C \quad (3-2)$$

The modeler contemplates the universal set objectively and methodically generates a first set of paths for a given *OD* pair, the *objective master set* \mathcal{M} (Frejinger et al., 2009; Van der Gun, 2013). Deterministic methods always generate the same path set \mathcal{M} . Most of them are derivatives of a repeated shortest path search and computationally attractive (Frejinger et al., 2009). Stochastic methods generate an observation specific subset \mathcal{M}_n , as the random element impacts outcome by observation n .

$$\mathcal{M}, \mathcal{M}_n \subseteq \mathcal{U} \quad (3-3)$$

Regardless of the generation method, a selective procedure determines feasible alternatives in the master path set (considered relevant by the researcher) for the user. This can be done deterministically or probabilistically, although defining choice sets in a probabilistic way is complex and has never been used in a real size application (Fiorenzo-Catalano et al., 2004).¹ Fiorenzo-Catalano et al. (2004) refers to the set of feasible alternatives as the *objective choice set* \mathcal{C} and is used as route choice model input.

Table 3-1 lists the route choice sets, following the example set in Van der Gun (2013).

Route choice set	Included alternatives	Symbol
Universal set	All possible routes	\mathcal{U}
Objective master set	Initial model set of routes	$\mathcal{M}/\mathcal{M}_n$
Objective choice set	Feasible routes	\mathcal{C}_o
Subjective choice set	Known to user	\mathcal{C}_s
Considered choice set	Included by user in route choice	\mathcal{C}_c

Table 3-1: Route choice sets and included alternatives (from large to small).

Although existentially different, the boundary between the considered choice set and the subjective choice set is not unambiguous and difficult to attain (Hoogendoorn-Lanser, 2005). Therefore and for the sake of simplicity we assume that users consider all routes that they are aware of in their route choice.

$$\mathcal{C}_c = \mathcal{C}_s \quad (3-4)$$

¹See Frejinger et al. (2009) for literature examples regarding probabilistic methods

Ideally, the objective choice set for an OD pair contains at least the subjective choice set, or in the case of a population of users, the union of subjective choice sets of users between that origin and destination (Fiorenzo-Catalano et al., 2004). This becomes evident when considering the relationship between the subjective choice sets and actual observed route set, as the latter is an implicit result of the first. As the number of observed routes missing in the observed objective choice set increases, the accuracy of the model diminishes. The *joint subjective choice set* \mathcal{J} for a population of users i is expressed in 3-5.

$$\mathcal{J} = \bigcup_i \mathcal{C}_{s,i} \quad (3-5)$$

$$\mathcal{J} \subseteq \mathcal{C} \quad (3-6)$$

As mentioned before, the set \mathcal{C} ideally contains set \mathcal{J} as this would mean that set \mathcal{C} is representative for the entire group of users. The modeler may attempt to identify the set \mathcal{J} by conducting surveys, although stated preference is always subjected to bias (Fiorenzo-Catalano, 2007).

A different approach is validating the objective choice set using the actual routes taken. We can identify the actual observed route set \mathcal{X} . This set contains the actual routes taken for that OD pair and thus is subsequently a subset of the joint subjective choice set \mathcal{J} . As the set \mathcal{X} contains all routes identified as used by users, the ideal objective choice set \mathcal{C} fully overlaps set \mathcal{X} .

$$\mathcal{X} \subseteq \mathcal{C} \quad (3-7)$$

Unfortunately, in practice the set \mathcal{C} does not fully overlap with the set \mathcal{X} , meaning that some actual observed routes are not included in the model ($\mathcal{X} \setminus \mathcal{C} \neq \emptyset$), while on the other hand the set \mathcal{C} may include unused routes which are not part of set \mathcal{X} (ergo: $\mathcal{C} \setminus \mathcal{X} \neq \emptyset$) (Fiorenzo-Catalano, 2007). However, according to Fiorenzo-Catalano (2007), it is better to erroneously include an unused route than to erroneously exclude or miss a used route.

The objective is, in order to approximate the ideal route set per connection, to generate an objective choice set \mathcal{C} where the number of actual observed routes missing is minimal and thus the coverage Ω of the objective choice set is as close to 100% as possible.

3-2 Network perspective

The measure of connection quality from a network perspective is referred to as the connectivity of the connection. In order to determine an indicator for connectivity or connection quality,

the aggregation of routes to a single representative value is necessary. In this section, a measure for the aggregation of travel times is assembled, based on conventional aggregation techniques.

We can establish a set of criteria where the measure must comply with:

1. **Number of alternatives.** The measure must take into account the number of alternatives available. More alternatives should have a positive effect on the outcome of the measure.
2. **Dispersion.** Increased dispersion of travel times of the route set should have a negative effect on the outcome of the measure.
3. **Stability.** The measure must be stable. As the number of alternatives increases, the effect measured must become less. The difference between for example 30 and 31 alternatives is negligible, which must be represented in the outcome. For the dispersion of travel times, increase should always have an increasing negative effect on the outcome, although this effect must not diverge unrealistically.
4. **Freeflow reference.** The measure should not only take the dispersion of travel time into consideration, but also the actual delay compared to the reference value. This reference can be determined at the discretion of the modeler.
5. **Not case specific.** The measure and involved parameters are preferably not case specific, thereby being less representative for alternate cases.

An explanation of conventional techniques is provided, followed by the determination of the aggregation method based on the criteria and the final assembly of the connectivity indicator. The connectivity indicator provides an analytic measure of aggregation per observation t over a predetermined interval T .

3-2-1 Conventional aggregation methods

Two conventional aggregation methods can be identified. The first method is the scaling of the route travel times using a type of weight attribute. An example would be using the probabilities, derived from a route choice model, as a weighting scale. This results in a weighted or scaled mean travel time distribution on OD level. The other method is a derivative of the route choice model, where instead of a weighted mean the aggregate quality can be determined using the logarithm of the divisor of the logit model. We refer to this second method as the 'Logsum' method (De Jong et al., 2005). Important to note is that both models are using travel time as input in this thesis.

Scaled mean method

The scaled mean approach gives an average view of the connection based on the assignment probabilities determined by the route choice model. However, as the method assumes an average condition it does not show the benefits of having multiple route options. In fact, by taking a scaled average the method disproportionately assigns ‘weight’ to the slower routes thus leading to a, by definition, higher aggregated travel time for the connection than that of the minimum. This can be illustrated with a simple example where we aggregate a connection of 2 routes, r_1 and r_2 . When the travel times of both routes are equal ($\tau_1 = \tau_2$), the scaled mean method determines the correct value for the aggregated travel time ($\tau_1, \tau_2 = \tau_{agg}$). However, when the travel times of the routes are not equal, the method finds an aggregated travel time that is always higher than the minimum travel time of the two routes $\tau_{agg} > \min(\tau_1, \tau_2)$. This is neither depending on the assignment probabilities nor on the amount of routes. The exemplary connection of two routes is also illustrated in figure 3-1.

Consider a connection with n number of routes and a probability distribution assigned to each of the routes. Also, again we assume a single route to be the fastest, τ_θ .²

$$\tau_\theta \leq \tau_i \quad \forall i \neq \theta \quad \text{since} \quad \tau_\theta = \min(\tau_1, \tau_2, \dots, \tau_n) \quad (3-8)$$

For the aggregated travel time this means the following:

$$\begin{aligned} \tau_{agg} &= p(p_1) \cdot \tau_1 + p(p_2) \cdot \tau_2 + \dots + p(p_n) \cdot \tau_n \\ &= \sum_n p(p_i) \cdot \tau_i \end{aligned} \quad (3-9)$$

$$\begin{aligned} &\geq \sum_n p(p_i) \cdot \tau_\theta \quad \text{where} \quad \sum_n p(p_i) = 1 \\ &\geq \tau_\theta \end{aligned} \quad (3-10)$$

As a result, the scaled mean method is an adequate method to determine the scaled average travel time condition of the connection based on the assignment probabilities of the route choice model, yet fails to capture the benefits of having multiple options in a connection. In fact, having more alternatives, leads by definition to a larger value.

²Note that it is possible that $\exists \tau_i = \tau_\theta$ when multiple routes are the fastest and equal. This has no consequence for the result, however this is why a less-than/equal-to relation is necessary in (3-8).

Logsum method

The Logsum method is a measure of consumer surplus in the context of logit choice modeling (De Jong et al., 2005). The scaling is based upon the exponent of the path travel times, instead of scaling by probability. Basically, the Logsum method uses the divisor of the logit model as the aggregate quality indicator and corrects for the exponents with a logarithm. The Logsum calculation method is shown in equation (3-11). The same as with the scaled mean method we assume $\tau_{t,p}$ to be the travel times $\forall p \in \mathcal{C}$ for an observation t . Also note that the fraction at the beginning corrects for the ϕ parameter of the applied logit model.

$$\tau_{agg,t}^{LS} = \frac{1}{\phi} \ln \left[\sum_{p \in \mathcal{C}} \exp(\phi \cdot \tau_{t,p}) \right] \quad (3-11)$$

The Logsum method, to the contrary of the scaled mean method, gives an close estimation of the minimum travel time. As the travel time of routes larger than the minimum route travel time increases, their respective share in the aggregate travel time decreases. In figure 3-1 the representation of the Logsum is illustrated, along with the scaled mean method and the minimum route travel time for an exemplary connection consisting of two routes. The aggregation is based on all routes, instead of just the minimum travel time and still simulates an aggregate travel time close to the minimum route travel time. Figure 3-1 also shows that when the travel times of both routes are (close to) equal, the measure presents a value below the minimum travel time. When the number of equal travel time alternatives increases, the value decreases, thereby assigning a ‘bonus’ for having multiple alternatives.

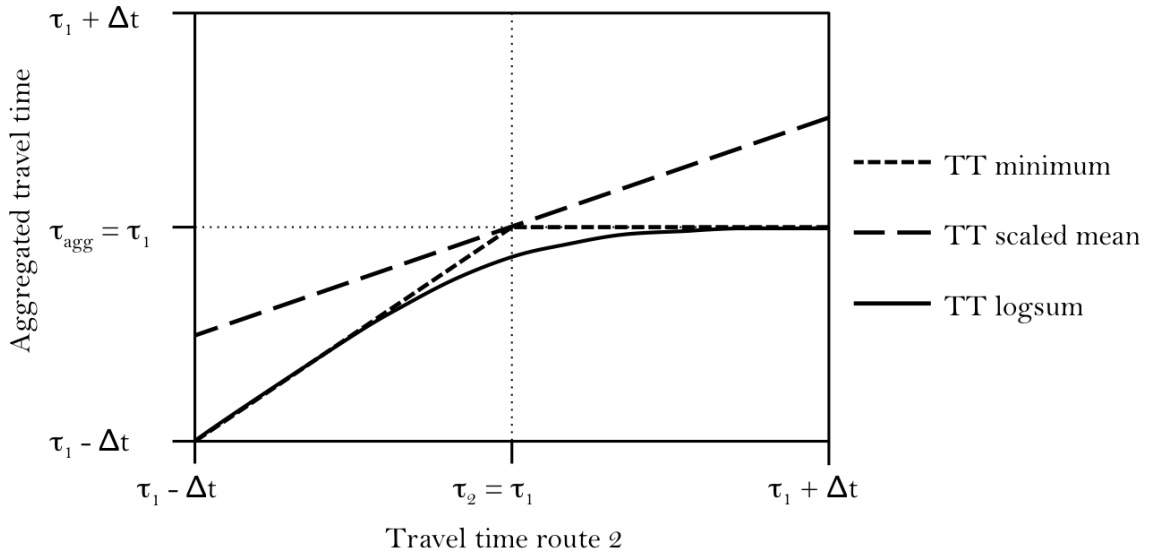


Figure 3-1: Exemplary illustration of two aggregation methods

3-2-2 Indicator based on travel time

This part elaborates on the assembly of an analytic measure to assign a value to the connectivity of a connection, thereby considering the conventional methods as described in the subsection before. We refer to this from now on as the ‘(dis)connectivity indicator’.

For an analytic aggregation of routes and based on the criteria as listed above, the scaled mean method is inherently inappropriate. The increase in number of alternatives has an adverse effect on the aggregated result. More alternatives leads to a lower score. Also, see figure 3-1 for an illustration. Furthermore, the assignment probabilities are based on a route choice model that is estimated based on a case study or on literature. Therefore, the result might not be representative of the investigated case.

The Logsum method is not based on assignment properties and is therefore not dependent on the estimated route choice model. Furthermore, the Logsum shows improvement of the aggregated results when more alternatives are considered and it is possible to implement the method with different types of input (e.g. travel times, relative travel times, utility values). Although this measure is theoretically justified and overall shows behavior in line with the criteria, the basic formulation of the Logsum method shows significant disadvantages.

The basic formulation of the method shows an absolute dependence on the number of alternatives, which is independent of the values of the input. We contemplate an example where all paths have the same travel time τ , but the number of alternatives n is variable:

$$\tau_{agg} = \frac{1}{\phi} \ln \left[\sum_n \exp(\phi \cdot \tau_i) \right] \quad (3-12)$$

$$= \frac{1}{\phi} \ln \left[n \cdot \exp(\phi \cdot \tau) \right] \quad (3-13)$$

$$= \frac{1}{\phi} \left[\ln(n) + \ln(\exp(\phi \cdot \tau)) \right] \quad (3-14)$$

$$= \frac{1}{\phi} \left[\ln(n) + \phi \cdot \tau \right] \quad (3-15)$$

$$= \underbrace{\frac{1}{\phi} \ln(n)}_{\text{Constant over } \tau} + \tau \quad (3-16)$$

This shows the constant part is dependent on ϕ and n , but has no relationship with the input, which is in this exemplary case the travel time τ . Although it is desirable that having more alternatives influences the aggregated result positively, the degree of this influence depends on the size of the input value. This effect can be considered undesirable. When we once more consider the example and assume multiple values for τ and compare this with the relative influence of the n -dependent part of equation (3-16), it can be concluded that this results in

a relative contribution dependent on the size of the input values, as is illustrated in figure 3-2.³

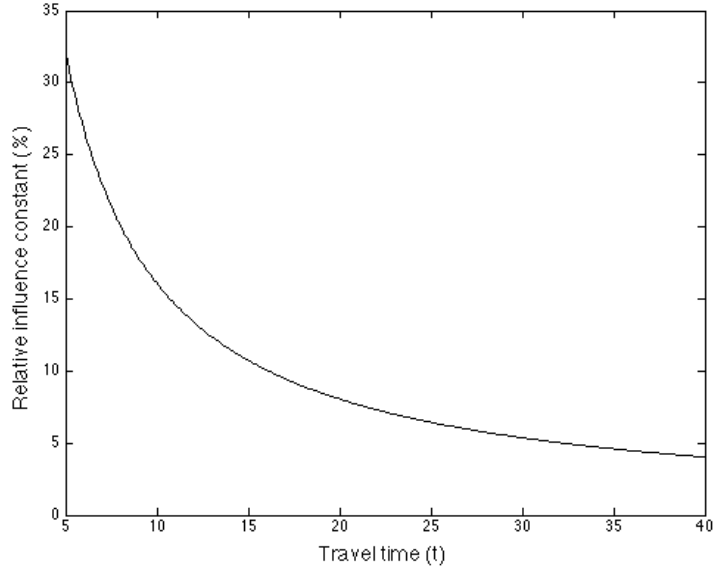


Figure 3-2: Relative influence of constant part of the Logsum ($n = 5$, $\phi = -1$).

For lower travel times the influence of having more alternatives is notably larger than for larger values. This suggests that the influence of having more available alternatives is significantly larger than when travel times are longer. This size-dependence can be considered counterintuitive, as for longer travel times and thus usually longer distances a larger network density can be expected with more alternatives. At a larger network scale, the lack of alternatives is likely to affect a larger number of network users. The size-dependence shown in figure 3-2 is therefore converse and not in line with expectation. Besides, the result of equation (3-16) may lead to negative values when the input values are too small.

In order to compensate appropriately for this dependence, redefinition of the basic formulation is necessary. Based on Ben-Akiva and Lerman (1985), redefinition of the basic formulation of the Logsum method for travel time gives the definition described in equation (3-17)

$$\tau_{agg,t}^{LS} = \bar{\tau}_t + \frac{1}{\phi} \ln \left[\frac{\sum_{p \in \mathcal{C}^{r,s}} \exp(\phi \cdot (\tau_{t,p} - \bar{\tau}_t))}{n} \right] + \frac{1}{\phi} \ln(n) \quad (3-17)$$

where $\bar{\tau}_t$ is the average travel time over all paths p for observation t . The Logsum method has been redefined into three parts: (1) an average travel time, (2) a part that aggregates the variable parts with respect to the average value and (3) the constant value as defined

³A hypothetical connection of $n = 5$ alternatives is considered, while ϕ is set to -1.

in equation (3-16). This redefinition shows that the main reason for size-dependence is the relative distance between part 3 and the mean value of the input in part 1. Over all the connections not the dispersion with respect to the mean is of interest, but the dispersion of the delay, or in other words the difference between the measured travel times on the routes and the reference value τ_{ff} , the freeflow travel time of the fastest freeflow route. From here, we can redefine equation (3-17) as depicted in equation (3-18).

$$\tau_{agg,t}^{LS} = \Delta\bar{\tau}_t + \frac{1}{\phi} \ln \left[\frac{\sum_{p \in \mathcal{C}^{rs}} \exp(\phi \cdot (\tau_{t,p} - \tau_{ff} - \Delta\bar{\tau}_t))}{n} \right] + \frac{1}{\phi} \ln(n) + \tau_{ff} \quad (3-18)$$

where $\Delta\bar{\tau}_t$ is the mean of the differences $\tau_{t,p} - \tau_{ff}$. In the same way, the basic formulation of the Logsum can be adapted, which is depicted in (3-19).

$$\tau_{agg,t}^{LS} = \frac{1}{\phi} \ln \left[\sum_{p \in \mathcal{C}^{rs}} \exp(\phi \cdot (\tau_{t,p} - \tau_{ff})) \right] + \tau_{ff} \quad (3-19)$$

Note that the aggregation is now based on the difference between the route travel time and the freeflow time of the fastest freeflow route. This way comparability over all observations $t \in \mathbb{T}$ is ensured, as size-dependence is now the same despite the length of the route. The addition of the constant has no influence on the behavior of the measure and it remains therefore theoretically justified.

Besides the dependence on number of alternatives and the value size, we can determine the behavior of the measure in respect to dispersion and how this effect is related to the effect of the number of alternatives. Consider a hypothetical scenario where the minimum travel time on all routes is $\tau = 15$, $n = [2, 3, \dots, 20]$ to be the number of alternatives, m the number of elements in n and the model parameter $\phi = -1$. The dispersion is depicted in 3-20.⁴

$$\underline{D}_i^n = \tau + n_i \omega \varepsilon_i^{disp} \quad \forall i \in \{1, 2, \dots, m\} \quad (3-20)$$

and where ω is the order of magnitude of dispersion of the example, in this case set to 0.5 and $\varepsilon_i^{disp} \sim \text{Unif}(0, 1)$ a random parameter simulating the dispersion. Note that the number of elements in D changes as the number of alternatives change. Figure 3-3 illustrates how the value of the Logsum changes with the number of alternatives and the dispersion as depicted in 3-20 for the hypothetical scenario. The Logsum values presented are normalized and the values are averaged over 500 simulations, since a random parameter is used⁵.

⁴ $n = 1$ is left out as the value of the outcome is arbitrary.

⁵The value of the Logsum is normalized for comparability by dividing by the maximum value in this example.

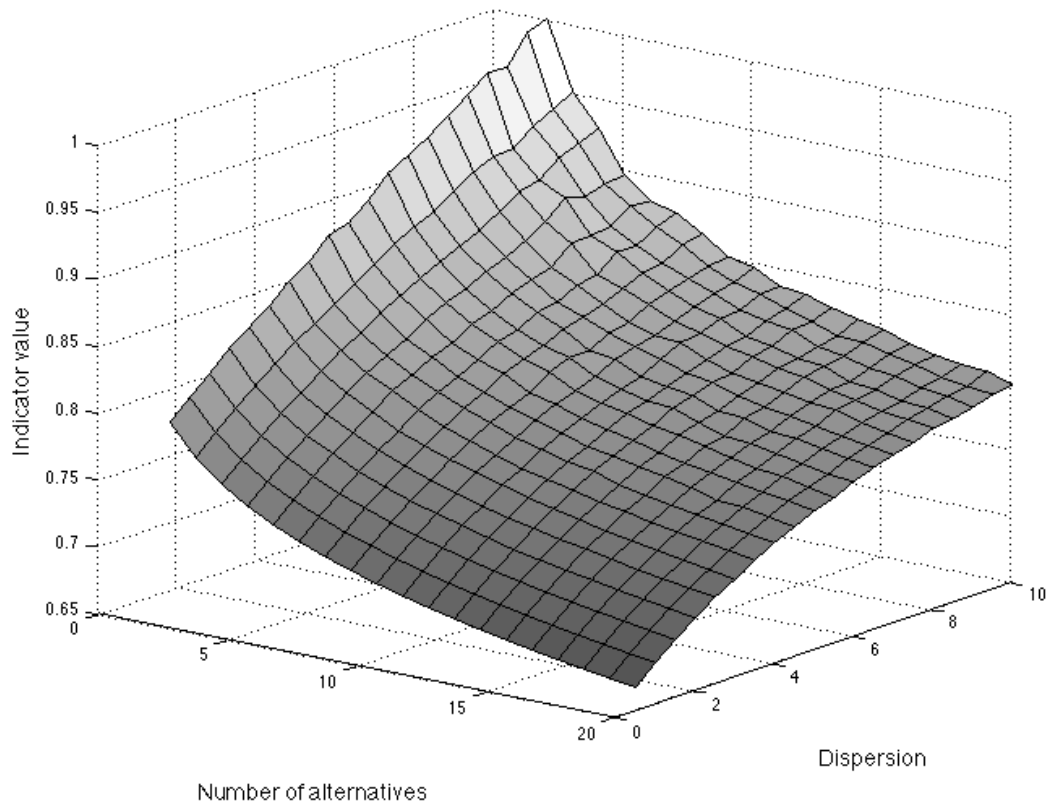


Figure 3-3: Normalized values for the redefined Logsum set against the number of alternatives and the travel time dispersion ($\phi = -1$).

Figure 3-3 shows that the outcome is sensitive to both the number of alternatives and the dispersion of travel time. It can also be noted that with current model settings the outcome value is slightly more sensitive to the dispersion than to the number of alternatives. When decreasing the value of model parameter ϕ , this relative sensitivity can be adjusted, thereby making the outcome more sensitive to the number of alternatives.

With regard to the redefined Logsum measure, we can conclude the following:

1. The measure is balanced. It is not overly sensitive to either the number of alternatives or the dispersion of travel time.
2. The method remains stable when the delays and number of alternatives increase. The addition of the fastest freeflow travel time does not alter the behavior of the measure and makes sure the outcome value is always positive for practical reasons. However, the method is not bounded and will become unstable when the value goes to infinity or minus infinity. For practical purposes this is of no consequence.

3. As the differences in travel time compared to the freeflow time of the fastest freeflow route increase the value of the aggregate increases as well.
4. As the number of alternatives increases, the derivative of the aggregate becomes gradually less. This is in accordance with the expectation that at some point the effect of having multiple alternatives becomes negligible. This degree of this mitigation over n is dependent on the model parameter ϕ .
5. As the delay or the travel time dispersion increases, the value of the aggregate shows almost linear increase. This is in accordance with the fact that the negative effect of delay does not mitigate as it increases. More dispersion should always negatively impact the measure outcome.
6. Model parameter ϕ can be chosen in accordance with research purposes or expert opinion.

Mathematical substantiation of the stability conclusions can be found in Appendix B.

The final addition necessary is the compensation for the difference between connections. The distance and travel time between OD -pairs can be significantly different and the value of the Logsum is dependent on this. Therefore, it is better to use a relative measure that compensates for this difference. In this case, this perspective can be added by, once again, including the freeflow of the fastest freeflow route as depicted in equation (3-21), thereby completing the connectivity indicator I_t^{conn} . Note that this value is still per observation $t \in T$ and that this addition does not influence the stability or behavior of the method.

$$I_t^{conn} = \frac{1}{\phi \tau_{ff}^b} \ln \left[\sum_{p \in C^{rs}} \exp \left(\phi \cdot (\tau_{t,p} - \tau_{ff}^b) \right) \right] + 1 \quad (3-21)$$

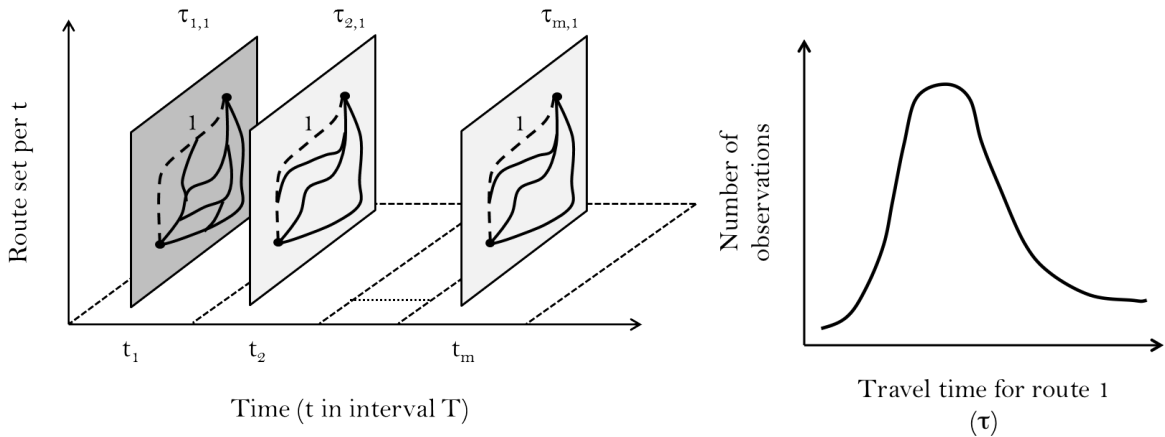
As the value of the connectivity indicator goes up, the lower the score for the quality of the connection.

3-3 User perspective

The quality and reliability of a connection from a user perspective is largely dependent on the choices of the traveler and the travel time distribution corresponding with those choices. In order to determine the perceived connection reliability from a user perspective, we observe a virtual user in a predetermined interval T . Within the predetermined interval T , we select a number of m observations $t \in T$ for which we determine the route(s) taken and the corresponding travel time distribution. The properties of the travel time distribution observed

depends on the routes taken. Where the connectivity indicator aggregates the routes per observation t , we now observe a single route per observation t and a corresponding travel time $\tau_{t,p}$. Depending on the type of user, the route observed at time t alters. Note that the route set does not necessarily remain the same at every observation t .

If we want to determine for example the travel time distribution $[\tau_{1,1}, \tau_{2,1}, \dots, \tau_{m,1}]$ for a traveler that always used route 1, we determine the travel time on route 1 at every observation t in the predetermined interval T . This is illustrated below in figures 3-4a and 3-4b.



(a) Route sets and travel time selection for route 1. (b) Travel time distribution for route 1.

Figure 3-4: Example of route sets and single route travel time distribution.

The example presented is now in fact a route travel time distribution as a single route p is observed, while at the same time it is representing a user always taking a single route for his trip. In other words, the example represents a trip travel time distribution of a user that uses only a single route. From here, it is also possible to establish a trip travel time distribution for a traveler y that uses multiple routes. This is illustrated in in figures 3-5a and 3-5b.

This second example is no longer dependent on a single route, but on the route choice of the user. From this, we can determine that the aspects of this distribution, such as the reliability, are dependent on route choice. Furthermore, as this type of aggregation of routes still leads to a travel time distribution, the reliability can be determined using (conventional) distribution based performance indicators.

3-4 Summary

In this chapter, first different definitions of route sets and the set required for aggregation are discussed. It is determined that the ideal route set can be approximated using route set generation. This approximation is referred to objective choice set. The degree in how well

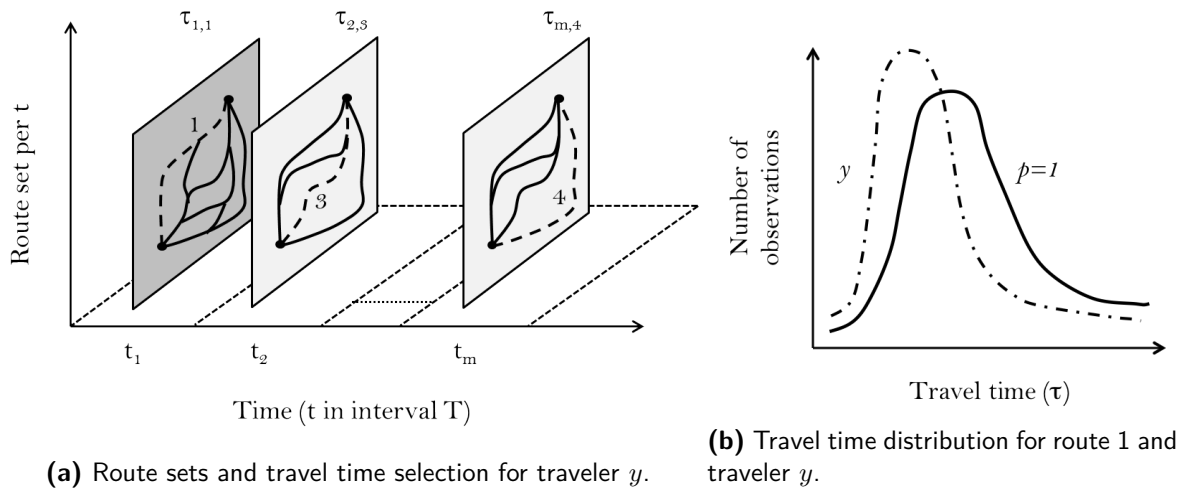


Figure 3-5: Example of route sets and travel time distribution of a combination of routes.

the ideal route set is approximated by the objective choice set is referred to as the coverage Ω . The objective is, in order to approximate the ideal route set per connection, to generate an objective choice set \mathcal{C} where the number of actual observed routes missing is minimal and thus the coverage Ω of the objective choice set is as close to 100% as possible.

For an evaluation of the network performance (network perspective) an adapted version of the Logsum method is introduced to the aggregate travel time distributions (combined over routes), thereby assessing the actual travel times of the routes and the number of alternatives within the route set. This measure is referred to as the connectivity indicator.

For the determination of perceived reliability, it is found that the assembly of a trip travel time distribution can be done similar to that of a route travel time distribution. It is also determined that the reliability of a trip travel time distribution is dependent on the routes taken by the user, or in other words on route choice. Furthermore, as this type of aggregation of routes still leads to a travel time distribution, the reliability of a trip travel time distribution can be determined using (conventional) distribution based performance indicators.

Chapter 4

Model design

This chapter provides a detailed explanation of the practical application of the proposed aggregation methodology from chapter 3 and other practical elements necessary for application. Section 4-1 explains the purpose of the model. It explains how the aggregation methods are implemented. Furthermore, it provides a direction for the investigation into the practicality and expressiveness of both aggregation methods and results. Section 4-2 gives an impression of the practical model framework and research limitations. Section 4-3 explains model parameters, references and indicators that are determined by the modeler, but are not case specific. Finally, section 4-4 provides a summary of the decisions and conclusions of the chapter.

4-1 Purpose and description of the model

The purpose of the model is to provide insight in the practical use of the proposed aggregation methodology in chapter 3 through the application of an exemplary model framework. The results of the designed model applied in a case study can be used to answer the practical application research questions.

In this designed model framework, the methodology is applied on several exemplary issues incorporating recurrent and non-recurrent events. As such, the methodology is applied during a peak hour interval and, as a reference, during an interval outside of the peak hour. The connectivity indicator is applied to determine how the connection quality depends on the time of day and the type of connection (proportion of urban and highway routes). The perceived connection reliability is determined for a uninformed, normal and fully informed traveler. Furthermore, the effect of having variable departure times on perceived connection reliability

is investigated by assuming a user with a static departure time and a user that has a certain predetermined time interval for departure.

Besides providing hypothetical answers to the practical application research questions, the results of the case study provide insight in the merit of applying the aggregation methodology in reality.

4-2 Model framework

In this section a model framework is designed for practical application of the aggregation methodology. Subsection 4-2-1 provides the algorithmic approach of the model, the practical application of the aggregation methodology. Subsection 4-2-2 determines predetermined limitations of the model design.

4-2-1 Algorithmic approach

The model design comprises two main parts: the model setup for applicability of the methodology and the application of the methodology itself. The model setup for applicability consists of the processing of data and the generation of a representative objective choice set through route set generation. The application of the methodology requires the determination of the model parameter for the connectivity indicator and the assembly of reference trip travel time distributions for the determination of perceived reliability. This setup is discussed in detail in section 4-3. The application of the methodology is done in an exemplary case study.

The algorithmic approach of the model framework is enumerated below:

1. **Establishing link based travel times.** Base data element is a network link. Aggregation of link travel times leads to route travel times. If travel times on route level are a priori present this step and step 2 and 3 are unnecessary.
2. **Route set generation.** Establishing the objective choice for a connection through route set generation. Criteria for route set generation are established here; the actual route set generator is case specific.
3. **Trajectories: from link based travel times to route based travel times.** The application of trajectories determines the actual travel times on route level.
4. **Connectivity indicator.** Determination of the effect of time of day and type of connection on connection quality.

5. **Perceived reliability.** Determination of how the level of information influences the perceived connection reliability. Reference distributions are established which are compared to a distribution corresponding to a fully informed user. Furthermore, the effect of variable departure times is investigated.
6. **Implementation of model framework for multiple OD-pairs using a case study.** The application of this model design in a case study.

These steps are illustrated in the model framework as presented in figure 4-1.

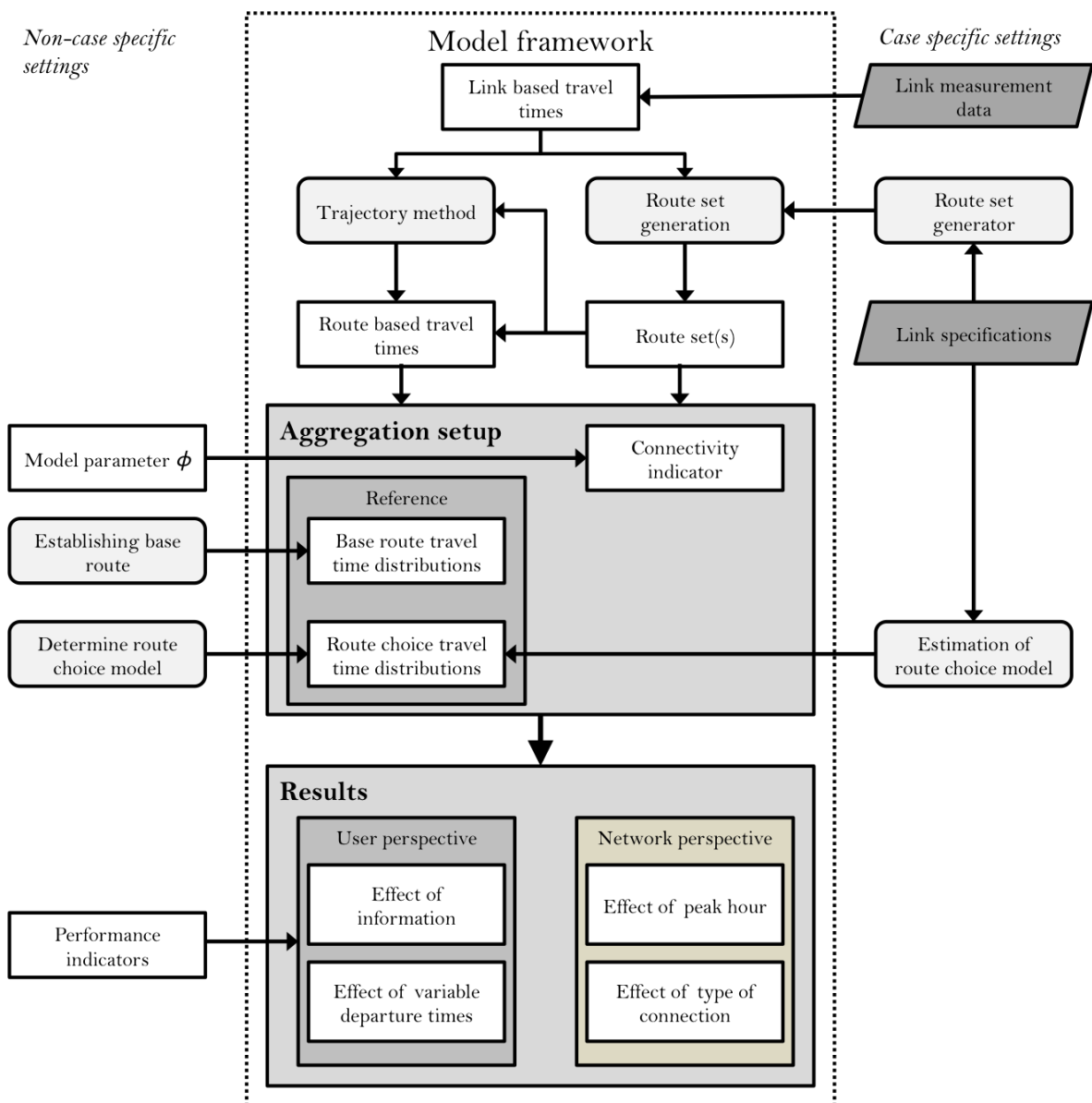


Figure 4-1: Model framework

4-2-2 Practical limitations

For the practical application of the designed model, we note the following limitations:

1. The research is single modal. Multi-modal aspects are not included.
2. The research does not specifically consider public transportation (PT); measurements of PT vehicles that use road infrastructure are generalized as normal road traffic.
3. No distinction is made between different types of travelers (e.g. gender, age, travel motivation, etc.).
4. A distinction is made between two levels of scale in the road network: *highway network* and *urban network*. Roads with maximum speeds above 70 km/h are considered highway, roads with maximum speeds below this threshold are considered urban.

Important to note is that these boundaries are set for practical purposes for the implementation of the model, not because of the proposed aggregation methodology.

4-3 Model setup

In this section the practical setup for the design of the model is explained, in order to complement the model framework presented. It also provides model settings that are determined at discretion of the modeler for the purpose of exemplary application, but are not case study specific. Section 4-3-1 presents different types of link based data and determines what kind is best applied for the purpose of this model. Furthermore, the trajectory methodology for the transition from link travel times to route travel times is explained. In order to determine routes for the trajectories, route set generation is necessary. Section 4-3-2 provides several conventional route set generation algorithms and determines a set of criteria the generated route set must comply with. The route set generator itself is case specific. In section 4-3-3 the final settings for the network connectivity indicator are determined, basing on a pre-determined balance between the number of alternatives in a route set and the travel time dispersion (not case specific). In section 4-3-4 the methodology for the determination of trip travel times is explained, as well as the determination of two reference scenarios: the base route, a representation of an uninformed traveler and a travel time distribution derived from a route choice model, a representation of a ‘normal’ traveler.

4-3-1 Data collection and trajectory method

In order to test the proposed aggregation methodology, input data for the model is required. Preferably, the method for reaching the thesis objective is implementable on multiple *OD*-pairs and even on other networks besides the case study used in this thesis. Therefore, availability of data and a uniform approach is of great importance. Both aggregation methods require route travel times, which can be derived from link travel times. For data collection, we establish a network link as our main network element for which data is gathered.

General description of data types

The type of data collection method employed to gather link travel times consequently determines the properties of the retrieved data and thereby influencing its expressiveness regarding the system. Each data type has certain endemic strengths and weaknesses. The generic data classes are: *floating car data*, *archived historical data* and *estimation/simulation techniques* (Lomax et al., 2003). Each of these types of data have specific properties, that determine their suitability for different objectives. According to Lomax et al. (2003), none of the data collection methods is comprehensive enough for all types of analyses and none of them include all the information required for a complete assessment of reliability issues. Table 4-1 shows the data collection properties.

Data collection methods	System coverage	Sample size	Time coverage	Individual	Bias
Floating car data	Small	Small	Small	Y	N ¹
Archived historical data	Large	Large	Large	N	N
Estimation/Simulation techniques	Large	-	Small	N	Y

Table 4-1: Data collection properties (based on Lomax et al. (2003))

System coverage:	Number of properties of the system measured (speed, capacity, travel time, intensity, density, etc.).
Sample size:	Number of observations per time unit (relevant for empirical data).
Time coverage:	Period of time covered.
Individual:	Data regarding a specific individual travel [Y: Yes, N: No].
Bias:	Is the data biased or subjective? (i.e. based on (questionable) assumptions or opinion) [Y: Yes, N: No].

Archived historical data is useful as the datasets are large and cover large quantities of the network and time. However, the data can be incomplete or partially erroneous, which have to be compensated for. Studies based on archived historical data can be validated by comparing to a floating car dataset as this does explicitly give individual user information (e.g chosen

¹The data itself is objective, however the subjective motivation of the user is unknown to the modeler.

routes and route travel time). Behavioral and forecasting studies occasionally use simulated datasets, assuming a distribution for the travel time. The emphasis is in this case not on the empirical, realistic accuracy, but on the method it proposes and tries to validate this by comparing it to other, already developed measures. However, this inevitably leads to assumptions about the distributions and thus biased results. Especially studies attempting an analytical approach (Ng et al., 2011; Clark and Watling, 2005) compromise significantly in order to save computation time by for example assuming independent link travel times, thereby for example missing spill back effects of congestion.

In this thesis we design the model basing on archived historical data, as it most widely available and has a large system coverage of network elements, over large periods of time. For the validation of the coverage of the generated route sets, floating car data is required.

Trajectory method

The use of archived data requires a transition from a large set of independent measurements to coherent, linked observations derived from the original data set. In order to ‘connect’ observations, we can assume an virtual user passing over the links in the network. As this user progresses over distance, time progresses. This so-called trajectory of the user can be simulated in the dataset as well, as the original set comprises multiple observations at different times. This trajectory is therefore a form of ‘individualization’ of the general dataset.

The mathematical definition of the trajectory method used (basing on Van Lint and Van der Zijpp (2003)) for the travel time $\tau_{t,p}$ for path p at a time t for a single OD pair is described below.

The travel time τ of a path p measured is the consecutive sum of the travel times of the separate links on the path, measured at time t . Mathematically, the basic definition of the trajectory method is therefore

$$\tau_{t,p} = \sum_{a \in A} \delta_a \tau_{t,a} \quad \text{where} \quad \delta_a = \begin{cases} 1 & \text{if } a \in p \\ 0 & \text{if } a \notin p \end{cases} \quad (4-1)$$

where $\tau_{t,a}$ is the link travel time at time t and δ_a a binary indicator indicating the presence or absence of link a in path p .

Note that for this basic definition the travel times on link level are already path and time dependent. When considering the set of independent measurements, an empirical definition of the trajectory method is required.

Let Γ_p be the link set for path p where $\Gamma_p \subseteq A$, where A is the set of all links in the network and j be the link index for all consecutive links $\forall a \in \Gamma_p$ with a total of n links in Γ_p .

Considering that the timing after link j (and thus the data point to be selected for link $j + 1$) depends on the travel time τ_j of the link j measured at the timing t_{j-1} (thus after finishing the previous link $j - 1$), we can determine that:

$$t_j = t_{dep} + \sum_{k=1}^j \tau_k(t_{k-1}) \quad \text{and} \quad t_0 = t_{dep} \quad (4-2)$$

where t_j is the time of departure at link j and t_{dep} is the departure time of the virtual user. The arrival time t_{arr}^p of the trajectory is at the end of path p where $j = n$ thus leading to:

$$t_{arr}^p = t_{dep}^p + \sum_{k=1}^n \tau_k(t_{k-1}) \quad (4-3)$$

Therefore, when considering the fact that the travel time $\tau_p = t_{arr}^p - t_{dep}^p$ for path p then this ultimately leads to the following simple equation:

$$\tau_p = \sum_{k=1}^n \tau_k(t_{k-1}) \quad (4-4)$$

There are two important aspects to consider when using the trajectory method. First, the aspect of algorithm stepsize compared to data step size. The second aspect is the relationship between the number of observations, the stepsize t_{step} and the time interval T . Both predicaments are explained in the following paragraphs.

The trajectory method can be employed multiple times in time interval T , preferably as many times as possible to increase the number of observations in time. We start at t_1 and select the closest data point \tilde{t}_{dep}^p on the first link of p . Then we perform the trajectory method and assume a new starting point in time, namely the beginning of the interval T plus a certain stepsize t_{step} . Then we again perform the trajectory method and so on for a total of n observations. The measurements in archived data sets are likely not continuous, but discretely divided over several time intervals. The size of a measurement interval can be considered the data stepsize t_{min} and is illustrated in figure 4-2.

Mathematically, the input for the trajectory method comes down to

$$t_{dep,\theta} = t_1 + \theta \cdot t_{step} \quad (4-5)$$

where $\theta = [0, 1, 2, \dots, n - 1]$. The empirical data point is located in a specific data interval from which the travel time value is determined. Also note that the departure time should be in the considered research time interval T (4-6a). From this we can determine that when $t_{step} \ll t_{min}$, the first data interval will be the same for multiple $t_{dep,\theta}$ and thus it is very possible only little changes are found in the resulting trajectories. Therefore, the stepsize of

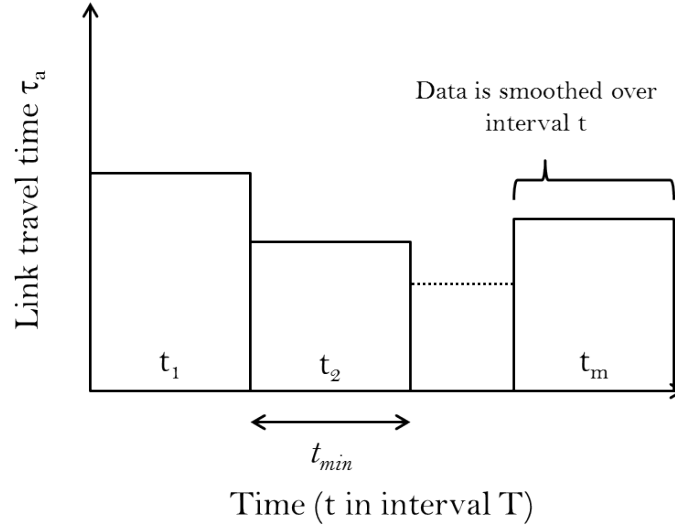


Figure 4-2: Data specification: measurement intervals

the trajectory method should be chosen in correspondence with the data step size in order to make sure the result is not too similar.

The departure time of a single trajectory t_{dep}^p on path p must be selected from the investigated time interval $T = [t_1, t_2]$. However, accounting for the amount of travel time needed and thereby making sure the entirety of the trajectory remains in T , the sampled departure time added to the travel time (ergo, the arrival time t_{arr}^p) may not exceed t_2 (4-6b). This is also illustrated in figure 4-3.

The boundaries for the trajectory method for a path p therefore become

$$t_1 \leq \tilde{t}_{dep,0}^p \quad (4-6a)$$

$$\tilde{t}_{dep,n-1}^p + \tau_p \leq t_2 \quad (4-6b)$$

where $\tilde{t}_{dep,0}$ is the sampled departure time for the first observation and $\tilde{t}_{dep,n-1}$ is the departure time of the final observation of a total of n observations.

With regard to the first aspect, we implement a stepsize for trajectory equal to the data stepsize. This way the sampled travel time on the first link always follows from a different data time interval per observation.

$$t_{step} = t_{min} \quad (4-7)$$

In consideration of the second aspect, n must be determined so that the final departure is

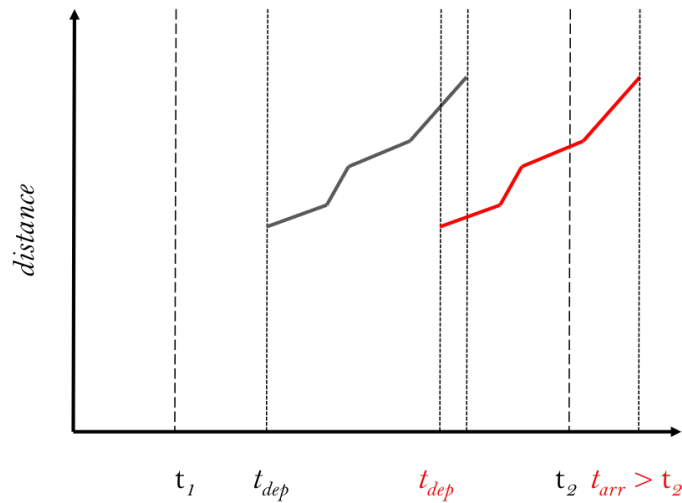


Figure 4-3: Illustration of erroneous sampling of t_{dep} .

sampled before t_2 (the end of interval T) without exceeding interval T , depending on the length of the trajectory.

4-3-2 Route set generation algorithm

In practice, the objective choice set \mathcal{C} can be generated using a variety of route generation algorithms. However, generated routes maybe circuitous or otherwise unsuitable for a particular OD pair and therefore it is necessary to identify a set of rules which the set \mathcal{C} must comply with (Bekhor et al., 2006). Important to note first is that in this thesis we consider not a particular user, but the set of users between that origin and destination. Therefore, the particular user specific properties are ‘integrated’ into a representative set, thereby including all the routes that any user might consider (Bekhor et al., 2006).

Descriptive list of algorithms

There are several current algorithms of which this section provides a short description.

The most well known shortest path finding algorithm is the Dijkstra algorithm (Dijkstra, 1959).² It determines a single shortest path between the OD pair, using link impedances. Based on this algorithm we can identify three popular route finding methods: the K -shortest Path³, the Labeling algorithms (Ben-Akiva et al., 1984) and *simulation methods*. Where the Dijkstra algorithm by itself is only suited for all-or-nothing assignment due tot its binary

²more information can be found in Dijkstra (1959).

³Bekhor et al. (2006) provides literary examples.

nature (i.e. it only finds a single shortest path), the other methods employ the algorithm in succession while altering the input parameters per run in order to find a set of paths.

Within the class of K -shortest Path methods, there are two popular heuristics that can be classified as *link penalty* and *link elimination* methods. Both techniques proceed iteratively after identifying a shortest path using the Dijkstra algorithm. In a link penalty heuristic, the link impedance on the shortest path is gradually increased. In a link elimination heuristic, links on the generated shortest paths are ‘removed’ from the network in sequence to generate new ‘virtual’ shortest paths and thus new routes.

The Labeling method of Ben-Akiva et al. (1984) employs multiple link attributes to distinct between routes. These link attributes, such as travel time, distance, functional class and driver experience (e.g. scenery, large number of traffic lights), can be utilized to determine different “generalized cost” functions in order to synthesize alternative routes. The created routes may be labeled according to the criteria (e.g. “minimize time”, “minimize distance”, “maximize use of expressways”, etc.) that yielded it, hence the name.

Simulation methods (of which Monte Carlo is a well-known example) produce alternative feasible paths by drawing impedances from different probability distributions, thus slightly changing the input based on a stochastic parameter. The distribution type (e.g. Gaussian, Gumbel, Poisson), distribution parameters, number of draws and the seed of the pseudo-random number generator are design variables. Note that the effectiveness of this method is directly correlated with computation time, requiring balanced design choices.

Other well-known route finding algorithms are *Branch and bound* (Land and Doig, 1960; Prato and Bekhor, 2006)⁴ and *Biased random walk* (Frejinger et al., 2009). However, the Branch and bound is not optimal for private mode networks (Van der Gun, 2013) and the Biased random walk method may include erroneous (circuitous) routes (Frejinger et al., 2009) and both methods are therefore a priori excluded.

Bekhor et al. (2006) evaluated the route finding algorithms based on the Dijkstra algorithm and found that individually all of the methods create route sets \mathcal{C} with insufficient coverage of the observed route set \mathcal{X} . Individual labels score below 30%, the K -shortest path heuristics score below 60% and Monte Carlo simulation scores below 50%.⁵

Furthermore, Bekhor et al. (2006) notes that combination of labels provides better results, yet since link attributes are likely correlated, for some OD pairs, the cost functions yield similar results (e.g. the least time path might be identical to the least generalized cost path). Therefore, we can determine that the coverage of multiple labels (m) is at least the maximum of the individual labels’ coverage, and at most the sum of each label’s coverage. This boundary

⁴For a (multi-modal) practical example we refer to Friedrich et al. (2001).

⁵Minimized simulated time with 48 draws (Bekhor et al., 2006).

is expressed in equation (4-9), where the coverage $\Omega(\mathcal{C}_M)$ of multiple labels is the coverage of the union of individual objective choice sets per label $\{\mathcal{C}_1, \mathcal{C}_2, \dots, \mathcal{C}_m\}$ (4-8).

$$\mathcal{C}_M = \bigcup_m \mathcal{C}_m \quad (4-8)$$

$$\min [\Omega(\mathcal{C}_1, \mathcal{C}_2 \dots \mathcal{C}_m)] \leq \Omega(\mathcal{C}_M) \leq \sum_m \Omega(\mathcal{C}_m) \quad (4-9)$$

In reality, the coverage of multiple labels increases as the number of different labels increases (i.e. if they are sufficiently distinct from each other), yet in case of a large scale network this method reaches a coverage of $\Omega \approx 70\%$ (Bekhor et al., 2006).

From this, we can determine that no single method is sufficient in order to generate a comprehensive objective route choice set. Following the example set in Bekhor et al. (2006), we select a combination of Labeling, K -shortest path and simulation in order to increase coverage. As the observed route set \mathcal{X} is a priori unknown it is necessary to validate the route set and, in case the coverage Ω is too low, additional adjustments are necessary.

Case setup criteria

In order to determine whether the route set generator is adequate a set of generator setup criteria is determined. For the determination of criteria, we can distinguish between algorithm properties and the resulting generated choice set. Basically, we can discern one major algorithm property: *computation time* (Bekhor et al., 2006). This property is significant when evaluating the practicality of the algorithm (e.g. when assessing a large network, large computation times limit the practicality). The generated objective choice set should comply with a number of practical rules (Fiorenzo-Catalano, 2007; Bekhor et al., 2006). First, the elimination of irrelevant (e.g. excessively large detours), identical (doubly generated routes) and erroneous routes (e.g. routes with circuitous elements). Second, a large variety of routes should be included, especially when considering the set should comprise different users. Third, the coverage of the objective choice set must be sufficient when comparing to the observed route set. Van der Gun (2013) also proposes ‘comparability of routes’ as criterion, however in case of single modal urban network we assume comparability to be sufficient.

4-3-3 Connectivity indicator

The outcome of the connectivity indicator is dependent on the number of alternatives and the travel time dispersion. The sensitivity of the outcome and how it is influenced by the variables is determined with the model parameter ϕ . In chapter 3, a hypothetical scenario for

the connectivity indicator is considered where $\phi = -1$. It can be noted that in this case the outcome value is slightly more sensitive to the dispersion than to the number of alternatives.

When decreasing the value of model parameter ϕ , this relative sensitivity can be adjusted, thereby making the outcome more sensitive to the number of alternatives. The parameter value of ϕ is set to -0.3 , thereby adjusting the sensitivity so that the effect of 10 minutes of dispersion has about the same effect as having 8 instead of 2 alternatives. This value is chosen at our discretion and can be adjusted in accordance with other research purposes or opinion. The effect of the model parameter ϕ is explained in more detail in Appendix C. Figure 4-4 shows the connectivity indicator with model parameter $\phi = -0.3$.

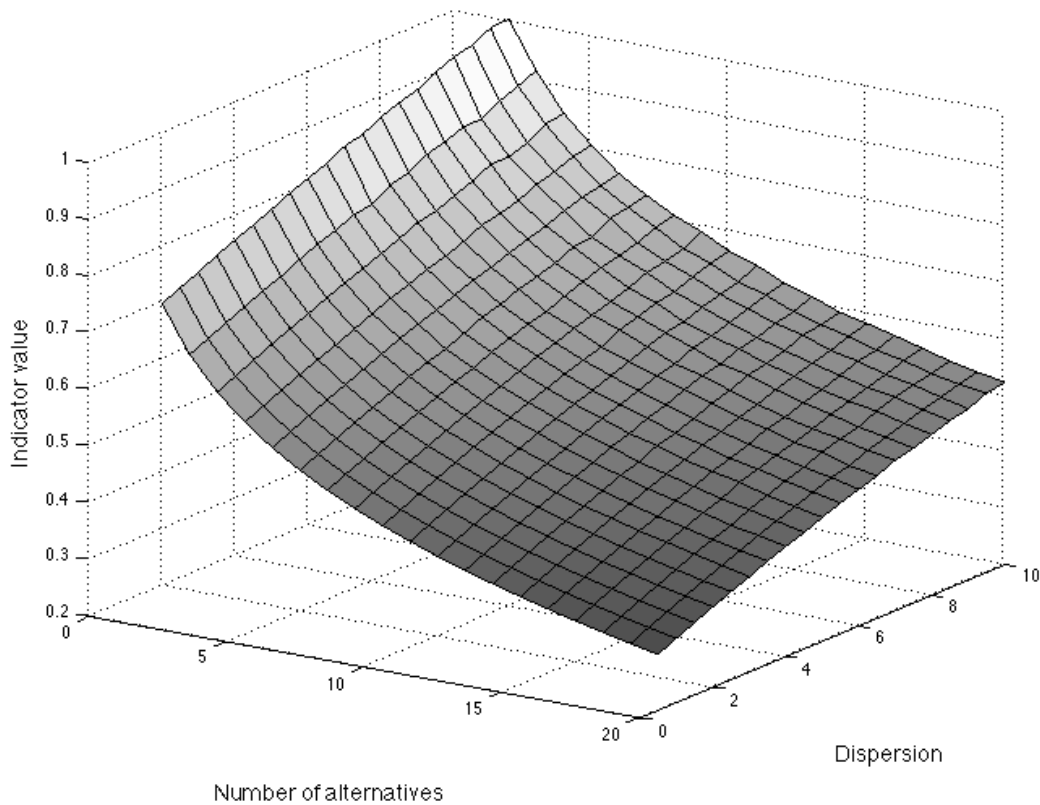


Figure 4-4: Normalized values for the redefined Logsum set against the number of alternatives and the travel time dispersion for $\phi = -0.3$.

4-3-4 Perceived connection reliability: base route, route choice model and performance indicators

Establishing a trip travel time distribution

In order to establish any travel time distribution (trip or route) a number of observations is required. When considering a predetermined interval T over multiple days, distinction must be made which observations are mutually comparable and thus suitable for aggregation.

For aggregation of observations over multiple days, three options can be considered:

1. **Interval T is assumed homogeneous. Days are comparable.** Interval T is considered to be homogeneous, thereby assuming that observations t within T are mutually comparable and that departure time in the interval is of no influence on the measures travel time. Besides, it is assumed that all the days interval T in investigated are mutually comparable. Technically, this means that all observations can aggregated into a single travel time distribution with $m \times$ days observations.
2. **Interval T is assumed homogeneous. Days are incomparable.** Interval T is considered to be homogeneous, the same as with option 1. However, days are incomparable, meaning that per day a distribution can be acquired.
3. **Interval T is assumed to be heterogeneous. Days are comparable.** The departure time or the observation t influences the travel time measures at that point. This means that when aggregating over multiple days, every observation t must be considered separately as the effect of the time of observation t within T is considered to be related to the travel time measured.

The options are illustrated in figure 4-5.

Although it can be argued that interval T is not homogeneous as at every departure the network may change, the same could be said when averaging over the days, as every day is different. Therefore, the choice of aggregation option is based on the purpose.

For the overall analysis of distributions for the determination of perceived reliability, option 1 is selected. In this situation, distributions are analyzed using the selected conventional performance indicators as described in section 2-4 and using the indicator for delay, which is described in more detail later in this section.

For the analysis of time-dependent measures, option 3 is selected. In this case, assuming a heterogeneous situation is necessary as the the measures are time dependent.

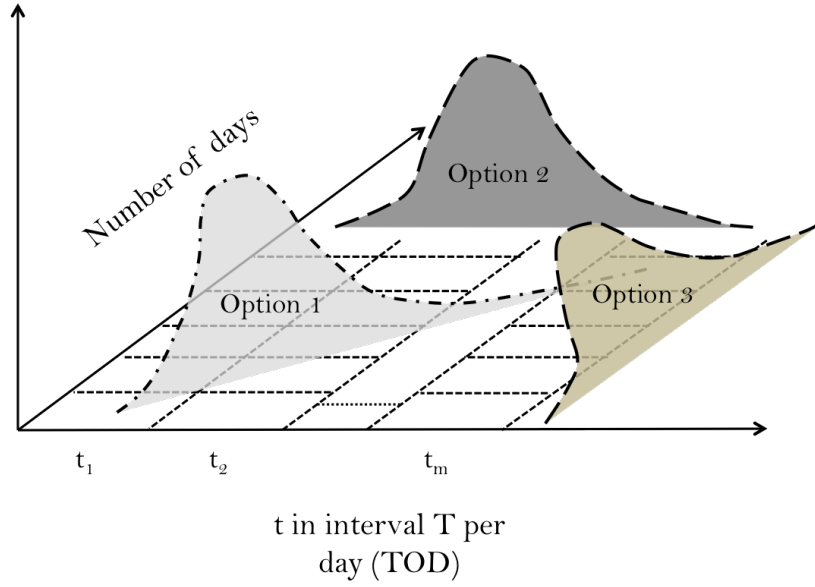


Figure 4-5: Aggregation options for time interval T

Base route travel time distribution

The base route serves as a proxy for a connection with a single route option or for a traveler that always takes the same route. It also represents a traveler who is uninformed of the connection and is therefore dependent on a single route. In the analysis of a connection for an OD -pair, we assume the base route to be a single route version of that connection, where no route switches are possible.

The base route travel time distribution thus consists of the travel time measurements at every observation $t \in T$ at a single path p . The selection of the base route depends on the comparison that the modeler wants to investigate. In this thesis, we assume the base route to be the fastest freeflow route of the connection. When multiple routes have the same fastest freeflow travel time, a random selection between these routes is made. The fastest freeflow route and its corresponding travel time τ_{ff}^b can be determined by assuming freeflow speeds on the network and a one-time application of the Dijkstra algorithm.

$$\tau_{ff}^b = \min[\tau_{ff,1}, \tau_{ff,1}, \dots, \tau_{ff,p}] \quad (4-10)$$

Travel time distribution based on choice modeling

Ideally, the utilization of a connection is completely known to modeler, indicating what routes are used more in comparison to others. Furthermore, in an ideal situation, the motivation for this subdivision among the routes in the connection is also determined. In practice, this

subdivision of users among routes in a connection is modeled using route choice modeling. The route choice model serves as indicator of the routes ‘normal’ travelers might take. This is embodied by a probability that a certain route is taken.

Not every route in the route set is of equal importance. As a matter of fact, two routes that only differ by a slight percentage of the total distance cannot be considered equally different to two non-overlapping routes. Therefore, it is preferable to use a model that incorporates this fact, without being overly complicated. Model practicality and accuracy is discussed by Bierlaire (2008).⁶ There it is concluded that the Path Size Logit is both practical and easy to compute and takes the overlap of routes into account. For the practical purposes of this model design, the Path Size Logit model suffices.

The formulation of the PSL component as follows

$$\text{PS}_p = \sum_{a \in \Gamma_p} \frac{L_a}{L_p} \frac{1}{\eta_a} \quad (4-11)$$

where

$$\eta_a = \sum_p \delta_{a,p} \quad (4-12a)$$

and

$$\delta_{a,p} = \begin{cases} 1 & \text{if } a \in p \\ 0 & \text{if } a \notin p \end{cases} \quad (4-12b)$$

and where L_a is the length of link a and L_p is the length of path p . Note that the value of PS is bounded by 1 (no overlap) and $1/n$ (complete overlap, duplicate route).

Besides the Path Size Logit formulation, we consider other components of the model that need to be incorporated. We use a utility formulation that incorporates, besides the PSL factor, the travel time (either mean or median), an indicator for travel time reliability (either standard deviation or the difference between the median and the 90th percentile) and finally the proportion of the route length using the highway (and thus consequently the proportion of usage of urban roads). Basic formulation for the logit model is

$$P(p) = \frac{\exp(\omega \cdot U_p)}{\sum_{i \in \mathcal{C}} \exp(\omega \cdot U_i)} \quad (4-13)$$

where U_p is the utility of path p . Note that ω is a model parameter and is determined at discretion of the modeler.⁷ The value of ω is set to -1, thereby assuming a high sensitivity to utility changes.

⁶Referenced literature can be found in this presentation.

⁷In conventional literature this model parameter is expressed by μ . In order to prevent confusion with the mean, a different expression is used.

The basic utility function can be formulated as

$$U = \sum_i \beta_i \cdot V_i \quad (4-14)$$

where β_i are the different parameters matching their respective components V_i .

Two formulations are considered for a path p : the first is based on mean-variance, the second is based on median-percentile.

$$U_{mean-variance,p} = \beta_{PS} \cdot \ln(PS_p) + \beta_{\mu} \cdot \mu_p + \beta_{\sigma} \cdot \sigma_p + \beta_{HW} \cdot \xi_{HW,p} + \beta_{urb} \cdot (1 - \xi_{HW,p}) \quad (4-15)$$

and

$$U_{median-perc,p} = \beta_{PS} \cdot \ln(PS_p) + \beta_{med} \cdot med_p + \beta_{perc90} \cdot \tau_{90\%-50\%,p} + \beta_{HW} \cdot \xi_{HW,p} + \beta_{urb} \cdot (1 - \xi_{HW,p}) \quad (4-16)$$

where for path p

$\ln(PS)$ = The logarithm of the PS factor

μ = Mean travel time

σ = Standard deviation

med = Median travel time

$\tau_{90\%-50\%}$ = 90% percentile minus the median travel time

ξ_{HW} = Proportion of path over highway

where each component listed is met with their respective β parameter. Note that in the utility function the logarithm of the PS-factor is taken. Due to its boundaries conditions, the value of the logarithm is always a negative value. As the PS-factor never reaches the value 0, the method remains stable. Furthermore, the proportion of the path over highway ξ_{HW} is a value between 0 and 1, where 0 means no highway taken and 1 means the complete path uses the highway. Consequently, the proportion of the road using urban roads is complementary to ξ_{HW} and is therefore $1 - \xi_{HW}$.

Selected performance indicator(s)

Basing on Pu (2011) and Wesseling (2013) and at our own discretion, we can determine the following set of relevant criteria in order to select travel time performance indicators for travel time distributions:

1. Simple and concise method. A simple measure with a concise and clear value is preferable over a complex method.
2. Increasing disutility as delays grow longer. The measure incorporates the length of the delay and assigns a proportionate value when delay increases, but takes skewness of the distribution into account.
3. Median based instead of mean based. The measure uses the median as it is less sensitive to outliers in the data.
4. No arbitrary parameters. The measure is not or little dependent on arbitrarily chosen parameters.
5. Well known, expressive and easily communicable. The measure must present a value that is easily understood and communicated.
6. Can be converted into a monetary value. Although not relevant in this thesis, in future research assigning a monetary value might prove necessary.

The conventional performance indicators and the criteria are listed in table 4-2. As no single measure complies with all the criteria, prioritizing of the criteria is necessary. The Buffer Index (median) complies with most of the criteria and is therefore selected. As monetizing can be relevant in the future, the standard deviation is selected as well, although it must be noted that this measure does not incorporate skew.

Each performance indicator is focused on a specific part of the distribution. The Buffer time Index represents the relative size of the tail of the distribution compared to the median. The standard deviation can be considered an indicator of the width of the distribution. Complementary, a measure must be added that has the main focus on the size and width of the peak of the distribution. An extra measure is selected that has this focus, without being overly influenced by the tail part of the distribution. From the statistical dispersion measures, the Mean Absolute Deviation about median (MAD) is selected (Elamir, 2012), expressed in (4-17)

$$D_{med} = \mu |\tau_i - med| \quad (4-17a)$$

$$= \frac{1}{n} \sum_i |\tau_i - med| \quad (4-17b)$$

Criterion	SD	COV	%RSD	BI(μ)	BI($\tau_{\%50}$)	PI	MI	Prob	SW
Simplicity	Y	Y	Y	Y	Y	Y	N	N	N
Proportionate value	N	N	N	N	Y	Y	N	Y	Y
Median based	N	N	N	N	Y	- ^a	N	- ^a	- ^a
No arbitrary parameters	Y	Y	Y	N	N	N	N	N	N
Expressive	Y	Y	Y	Y	Y	Y	N	Y	N
Monetary	Y	Y ^b	Y ^b	N	N	N	N	N	N

Table 4-2: Performance indicators and the criteria. Y: Yes, the indicator complies with the criterion, N: No, the indicator does not comply with the criterion. Based on Pu (2011); Wesseling (2013).

^a No mean or median of the travel time is employed.

^b Measures are based on the SD and therefore a (relative) monetary value may be derived.

where med is the median.⁸ This measure is simple, proportionate, median based and has no arbitrary parameters. Conversely, it must be noted that it not very expressive and cannot be expressed monetary.

Lastly, a measure that specifically indicates the extend of the delay suffered is determined necessary. In order to determine the extend and effect of differences in reliability, a measure to indicate the time lost during the observed time interval is developed. In this case, the time lost per connection is of interest. The measure indicates the delay on a connection level, thereby requiring travel time distribution and the difference between this distribution and a reference. In this case we again assume the fastest freeflow time of the fastest freeflow route as reference. The delays measured in the travel time distribution analyzed compared to this reference is then aggregated. Basic formulation is given in (4-18).

$$\tau_T^{loss} = \sum_{t \in T} (\tau_t - \tau_{ff}^b) \quad (4-18)$$

where τ_T^{loss} is the aggregate delay for the total of observations T and τ_t is measurement at observation t for specific travel time distribution. Note that the value is in this case dependent on the number of observations in the distribution. The more observations, the larger the aggregate value becomes. For relative comparison between distributions this holds no threat, however, it may jeopardize the generic aspect of the measure as comparison between research may determine a difference in size for T. Therefore, the value must be compensated for the number of observations $t \in T$.

In order to ensure comparability between different connections, another adjustment is necessary which is similar to the addition made in (3-21), where the difference is converted to a relative difference. Including this addition and the compensation for the number of observa-

⁸This measure can also be performed about the mean or mode. In this case the median is most relevant.

tions leads to the measure proposed in (4-19).

$$DI_T^{loss} = \frac{\sum_{t \in T} (\tau_t - \tau_{ff}^b)}{m \tau_{ff}^b} \quad (4-19)$$

where m is the number of observations $t \in T$. When no delay is measured over interval T , the value of the indicator is minimized. It holds that $\tau_t \geq \tau_{ff}^b$, leading to the 0 being the lower boundary of DI_T^{loss} . As the delay is in theory not bounded, the measure has no upper boundary.⁹

4-4 Summary

This chapter explained the practical setup and design of the model framework for the application of the proposed methodology in chapter 3. The results of the designed model applied in a case study can be used to answer the practical application research questions. In this designed model framework, the methodology is applied on several exemplary issues incorporating recurrent and non-recurrent events. The model can be applied during a peak hour interval and, as a reference, during an interval outside of the peak hour.

An algorithmic representation of the model framework is provided, as is a flowchart illustration of the model. A number of research limitations is enumerated.

For the basic model setup, it is determined that a combination of archived historical data and floating car data is the best for the application of the model. The archived historical data can be processed using trajectories to acquire route based travel times. The floating car data can be used for validation of route sets. For the generation of routes, a descriptive list of possible algorithms is provided with a set of criteria the case study route set generator must comply with.

The connectivity indicator is applied to determine how the connection quality depends on the time of day and the type of connection (proportion of urban and highway routes). The model parameter ϕ of the connectivity indicator is set to -0.3. The perceived connection reliability is determined for a uninformed and normal traveler (references) and for a fully informed traveler. The two reference distributions are represented by a base route (fastest freeflow route) and Path Size based route choice model travel time distribution, respectively. Furthermore, the effect of having variable departure times on perceived connection reliability is investigated by assuming a user with a static departure time and a user that has a certain predetermined time interval for departure.

⁹In theory, delay can be infinite, although in practice this is obviously impossible. However, no maximum delay can be determined and thus the measure has no upper boundary.

Case study: Amsterdam

This chapter elaborates on the practical application of the developed model framework in the municipal region of the city of Amsterdam, the Netherlands. This thesis has been performed in the context of a large-scale practical pilot application of a combination of comprehensive innovative traffic measures in this region under development at the moment of writing, referred to as the ‘Praktijkproef Amsterdam (PPA)’, or in English referred to as the ‘FTA’.

The chapter begins with background information regarding the FTA and the context of this thesis in this project. From there, the implementation of the model framework is explained, followed by the results generated.

5-1 Background

5-1-1 Case description

The ‘Field Trial Amsterdam’ is a trial application of traffic measures in attempt to reduce traffic congestion in the Amsterdam municipal region. It is a large-scale experiment with innovative use of technologies on the road, but also in-car in the form of route advice on the smartphone. Road users get personal route and departure time advice in the car in order to choose their optimal travel specifications and route. Normal traffic lights at intersections and traffic lights located at the on-ramps to the highway are coordinated to respond to traffic jam predictions. The goal is to get road users more quickly to their destination and that they can count on reliable travel times incorporating real-time traffic information (Rijkswaterstaat, 2014c; Stadsregio, 2014b). The project is coordinated by ‘Rijkswaterstaat (RWS)’, a part of

the Dutch Ministry of Infrastructure and Environment “responsible for the design, construction, management and maintenance of the main infrastructure facilities in the Netherlands” (Rijkswaterstaat, 2014a) in cooperation with the Municipality of Amsterdam, the province of Northern Holland and the ‘Stadsregio Amsterdam (City Region of Amsterdam)’, “a partnership between 16 municipalities in the Amsterdam region” (Stadsregio, 2014a).

The FTA consists of two main ‘practical tracks’: the *in-car track*, consisting of in-car system development, such as a routing application on the smartphone, and the *roadside track*, consisting on the roadside systems such as dynamic route information systems. Next to this, the trial is divided in two main ‘application tracks’: *general commuter traffic* in the region and *event traffic* in a specific part of Amsterdam (in close proximity of large scale event buildings, such as the Ziggo Dome and the Ajax football/soccer stadium) causing a high peak load on the network (Connekt, 2014).

On Monday, June 25th, 2013 the definitive decision was made to go through with FTA (Connekt, 2014) on all previously mentioned tracks. For the in-car part of the FTA, RWS selected two consortia of companies based on their proposal for implementation. The official granting was made public January 15th, 2014 (Rijkswaterstaat, 2014b). The consortia, Arcadis/VID and ARS/TNO, will conduct trials from mid 2014 until the end of 2015 with in-car information services. These trials are aimed at frequent users of the Amsterdam ring road A10 and the visitors of large events in the region (see figure 5-1). Basing on personal specifications and real time traffic information regarding route and parking facilities (event track only), road users are able to select an optimal route for the particular moment of request. Currently, the recruitment of participants is in progress (Rijkswaterstaat, 2014b).

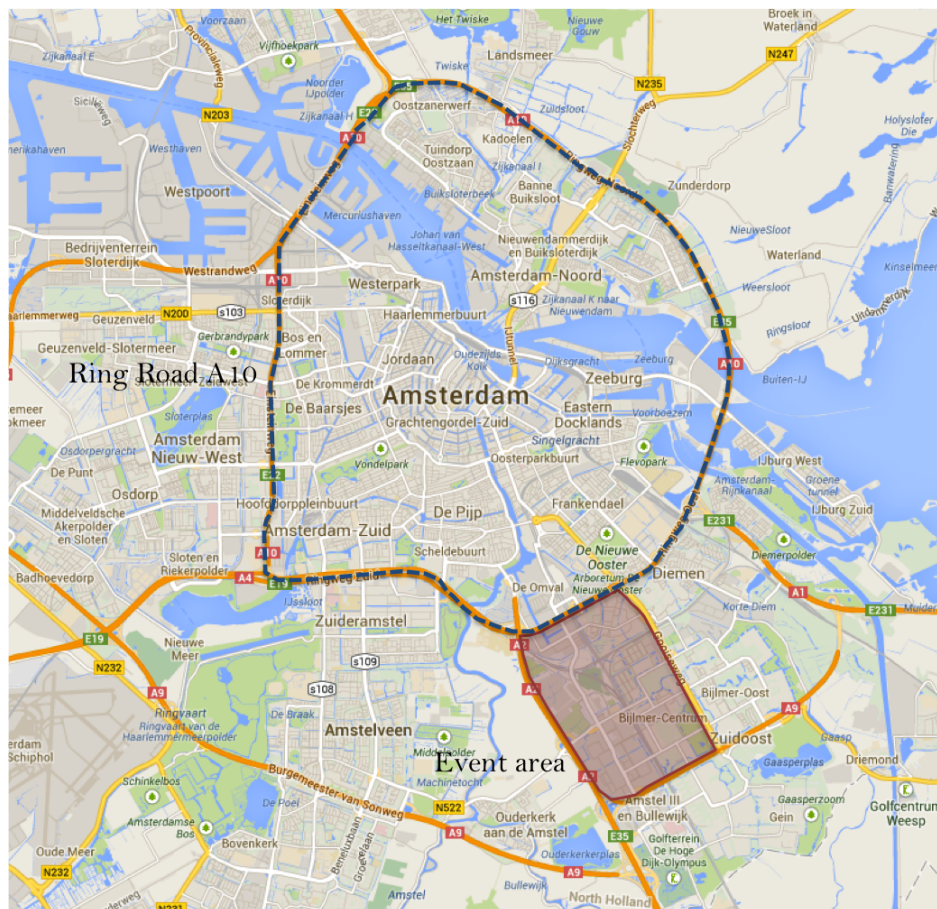


Figure 5-1: The target area with the ring road A10 and event area highlighted (Google, 2014)

5-1-2 Thesis relevance in practice

The objective and purpose of this thesis are unrelated to the FTA. However, the methods and data required to reach the objective of the FTA are in many ways similar and thus mutually beneficial. This holds especially for the in-car systems designed for the general commuter traffic, where similar steps are necessary in order to reach the objective.

Some of the algorithms used in this thesis are based on their FTA counterparts. This can be said regarding the route set generation.¹ In return, during the adaptation and utilization of these algorithms, this thesis offers feedback regarding accuracy and detection of errors.

The theoretical implementation of a fastest path algorithm in this thesis offers a perspective on the added value and effects of real life implementation. In fact, a traveler using fastest path advice takes the fastest route possible in current traffic conditions. Therefore, it is interesting to determine how the perceived quality of network changes for a person following this advice and how the travel time distribution of such a traveler is compared to a traveler that always

¹Based on work by Minderhoud (2014).

uses the same route or a ‘normal’ distribution based on choice modeling. Besides, the research can provide insight in the effect of variable departure times, which is relevant as the FTA also provides the user with an optimal departure time.

5-2 Network specifications

The case study network is based on the model network of Navteq, the Netherlands (Navteq, 2012). The model network is that of the complete road network of the Netherlands. Network details are provided in table 5-1 and 5-2.

Network element	Quantity
Single direction links	35056
Two direction links	10871
Total number of links	45927
Number of nodes	33062

Table 5-1: Network properties

Link level of scale	Quantity
Highway (speed \geq 70 km/h)	20304
Urban (speed $<$ 70 km/h)	25623
Total number of links	45927

Table 5-2: Link properties

For the purpose of this case study, the area in and around the city of Amsterdam is of particular interest. The model network in this area is illustrated in figure 5-2 (scale 1:500000).

5-3 Data and time specifications

Acquired data for the network is derived from the NDW (‘Nationale Databank Wegverkeergegevens’ or Dutch National Database of Road Traffic Data) (NDW, 2014). This is linked to the model network from Navteq, thereby making it possible to derive corresponding link data when requested. With regard to the nature and quality of the data, the following can be said:

Categorization of the data

The dataset can be categorized as *archived historical data*. The set is an elaborate collection of historical roadside data (e.g. speed, density, travel time, etc.), acquired from multiple data sources.²

²For the data collection methods used to gather data, we refer to the NDW.



Figure 5-2: Model network impression

Coverage

The coverage of the network is extensive. For the higher levels of scale, the acquisition of roadside data is sufficient over longer periods of time. At this scale data gathering is often continuous and automatic. For the lower levels of scale, measurements are often scarce as no roadside measuring is performed continuously and gaps in the data are more common.

The network and dataset are both covering the complete Dutch network, which means that for the route set generation no problems are expected with regard to the scope area and the possibility of accidentally creating routes outside the scope area. Besides, the implementation may extend beyond the Amsterdam area in future research to investigate other Dutch urban areas.

Technical data specification

Data is divided into measurement intervals with a single representative value for measurements in that time interval. Specifically, as all measurements from the different data sources are scattered over time, the measurements are assigned to a specific interval in the time they were performed. Within such an interval, all the measurements assigned to that interval are ‘smoothed’ to a single value for that interval.

The size of this interval is the data stepsize t_{min} , as mentioned in section 4-3-1. In this study the value of t_{min} is 5 minutes, meaning that all measurements made within that interval for

a specific link are smoothed to an average representative value. If no data is present, the algorithm assumes freeflow travel times on the respective routes.

We can consider a period in time, or the time interval T . Within this observed interval, are the measurement intervals $t \in T$, with a stepsize of $t_{min} = 5$ minutes. Depending on the size of the observed interval T , we find m intervals t .

Time scenarios

In the thesis we consider two main time scenarios: *Peak hours* and *non-peak hours*. Thereby, as peak hours are recurrent, we are considering the effects of these recurrent events on the network in the thesis. The effects of non-recurrent events, such as accidents or bad weather are not considered specifically and their effects are mitigated by considering multiple days and by choosing an appropriate travel time performance indicator that compensates for the outliers. Besides this, in order to improve the reliability of a sampling experiment using time intervals, it is recommended to choose multiple time intervals in multiple scenarios to compensate for the subjectivity of the initial choice (Li et al., 2009).

As the focus of the thesis is on a ‘normal’ workday, we sample multiple comparable days over longer periods of time. More specifically, only a specific day in the week is considered, as days are mutually different with respect to the usage of the network. In this thesis, we choose to consider multiple days for multiple years and in order to ensure comparability a single day of the week is chosen (e.g. Monday, Tuesday, etc.).³ Furthermore, we distinguish between three peak hours and three non-peak hours per day (the size of interval T is therefore interval 3 hours). Technically, we select a time interval T between two points in time:

$$T = [t_1, t_2] \quad (5-1)$$

where in case of the peak hour scenario $t_1 = 07h00AM$ and $t_2 = 10h00AM$ and for the non-peak hour scenario $t_1 = 12h00PM$ and $t_2 = 15h00PM$.

For a single scenario, peak hour or non-peak hour, with the current stepsize of $t_{min} = 5$ minutes, we observe within T , $m = 24$ intervals in a single day. This is done for both scenarios for the total of 43 Tuesdays in the years 2012 and 2013. Table 5-3 summarizes the specifications of the periods of time of measuring.

5-4 Investigated connections

For the purpose of this research, a selection of *OD*-pairs has been made. The center of Amsterdam has been selected as the main destination, with multiple origins connecting to

³The day of the week chosen is arbitrary and be exchanged if such is desired.

Aspect of time	Interval length or value	Note
Number of days observed	43	Tuesdays, Sept. 4, 2012 - June 25, 2013
Stepsize of departure times t_{min}	5 min	-
Interval T per day	3 hours	Peak: 7h00AM - 10h00AM, Non-peak: 12h00PM - 15h00PM
Number of intervals $t \in T, m$	24	First 2 hours of T divided by the stepsize

Table 5-3: Case specific periods of time of measuring

the center. For these 5 highway connections are selected and 4 urban connection (these do not use the highway, while the highway connections (may) partially use urban roads). This explicit distinction has been made in order to (1) test the difference between higher and lower network levels, (2) to test lower network levels for data validity, as this is usually more scarce than on a higher network level.

The origins are:

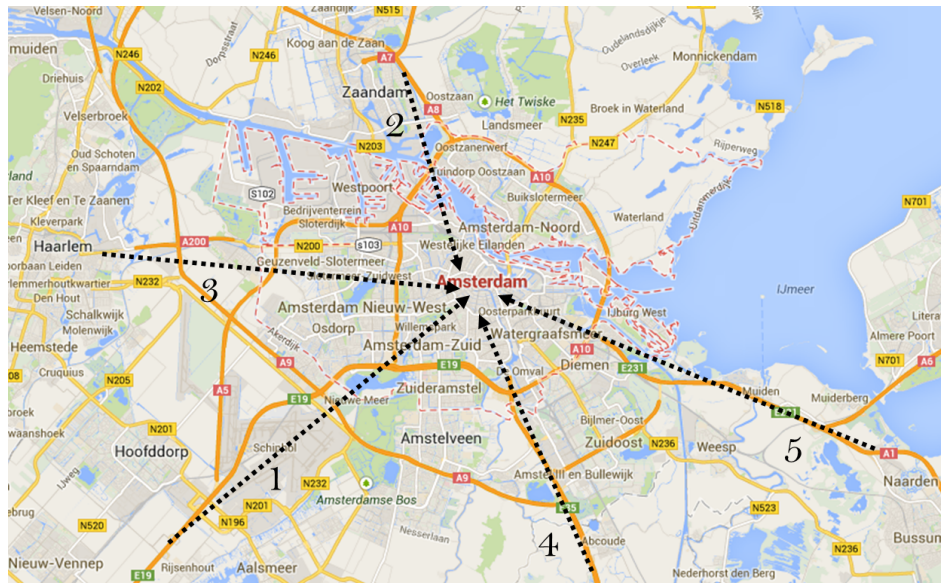
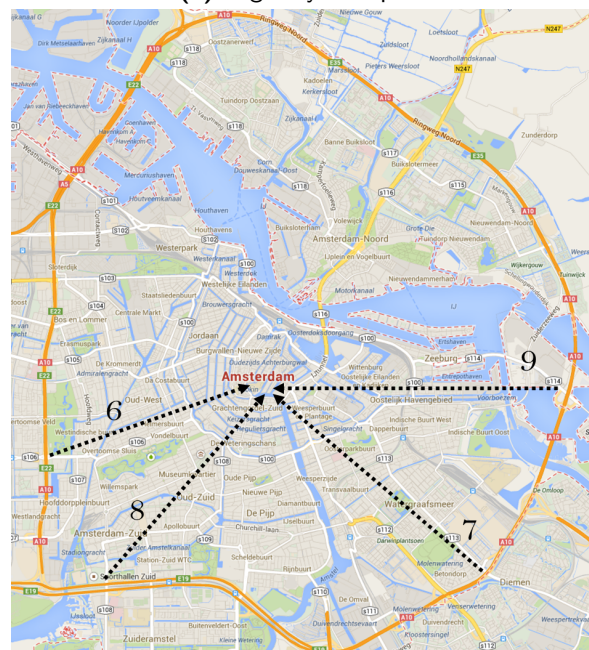
Highway

1. Direction South - Holland
2. Zaandam
3. Haarlem
4. Direction Utrecht
5. Direction Amersfoort

Urban

6. Amsterdam - West
7. Amsterdam - Southwest
8. Amsterdam - Southeast
9. Amsterdam - East

The origins and their direction towards the destination, Amsterdam - Center, are illustrated for both highway as urban connections in figures 5-3a and 5-3b, respectively. Note that an urban connection from Amsterdam - North is missing. This is because this area is connected with the center by a higher level of scale road. This would make the connection from this area incomparable with the other urban connections.

(a) Highway *OD*-pairs(b) Urban *OD*-pairsFigure 5-3: Investigated *OD*-pairs

5-5 Route set generator

This section discusses the implemented route set generation algorithm and procedure and the applied model settings.

5-5-1 Route set generator specifications

For the purpose of the research performed in this thesis, the route set generator has the following specifications:

1. The algorithm is Dijkstra based (Dijkstra, 1959).
2. The algorithm employs Labeling to determine the fastest route, the shortest route and the highest comfort route (highest proportion of highway). These are deterministic.
3. A derived form of the K -shortest Path method is used. Link elimination is performed a single time on the fastest route at the link around 50% of the routes distance.
4. After determining deterministic routes, links are subjected to a stochastic influence that slightly alters the measured travel time. After this ‘adjustment’, the algorithm determines whether a new route has become the shortest. This is done for a number of x simulations. Duplicate routes are eliminated. The type of links subjected by this stochastic influence can be manually adjusted based on the their freeflow speed. The manually adjusted model parameter ζ_{thres} determines the threshold to what links a stochastic influence is assigned. Links with freeflow speeds below the threshold are thereby not stochastically influenced. The value of ζ_{thres} can be set to 30, 50 and 80. The degree of stochastic influence is dependent on a manually set variance of the link travel time and depicted by model parameter ζ_{var} .⁴

This route set generation is performed at every observation $t \in T$, thereby acquiring multiple, variable route sets for a single connection of an OD -pair. The variability of the set is dependent on the state of the network and on the degree of stochastic influence on link level. As the route set is aggregated at every observation t , this variability is considered desirable as it increases the chance of a representative coverage. The downside can be considered the computation time, as the process of route generation is now repeated at every observation t . This process is illustrated in figure 5-4.

5-5-2 Model parameter settings

The number of routes and the variability of route set size generated per time interval t depend on a number of parameter settings as mentioned in section 5-5-1. Table 5-5 provides and overview of the model parameters and their respective values.

⁴The influence of the model parameters x , ζ_{thres} and ζ_{var} is investigated in Appendix C.

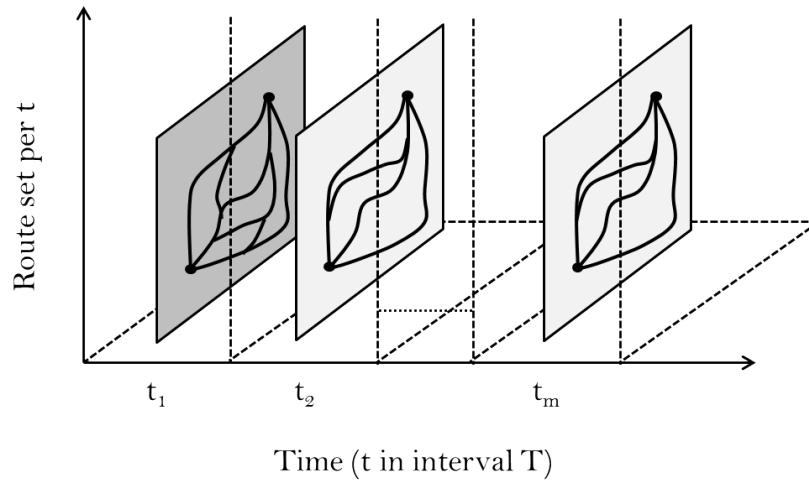


Figure 5-4: Route sets and variability per interval $t \in T$

Speed threshold

The threshold ζ_{thres} for the maximum speeds directly influences the amount of links that are stochastically influenced and are presented in table 5-4.

Value of ζ_{thres} (km/h)	Number of links with speed above threshold
0	45926
30	45926
50	27757
70	20304
90	5403

Table 5-4: Links included in stochastic simulation depending on the value of ζ_{thres}

It is considered unnecessary to add a stochastic influence on roads below 50 km/h, as at this scale travelers are unlikely to change route on a regular basis as this level is mostly used by destination traffic. Besides, the influence of congestion is likely not so much as it is on higher levels of scale. Roads of 50 km/h and higher are usually roads connecting different areas and are used by through traffic and thus more likely to influence route choice. Therefore, the value of ζ_{thres} is set to 50 km/h.

Link variance

The value for ζ_{var} also influences the number of routes generated. Although no apparent reference value could be found, it is safe to say that for example a variance of 100% of the travel time is unrealistic, as no traveler is willing to drive twice as long as the fastest route. Initial expert judgement would expect a value for ζ_{var} between the 0.10 and 0.4 times the travel time. In the model framework designed by TNO this value is set to 0.35 and we see

no apparent reason to deviate from this (Minderhoud, 2014). Therefore, the initial value for ζ_{var} is set to 0.35.

Number of simulations

The number of simulations x is set to 50 runs per generation.

Model parameter	Symbol	Value
Speed threshold	ζ_{thres}	50 (km/h)
Link variance	ζ_{var}	0.35
Number of simulations	x	50

Table 5-5: Overview of route set generation parameters and corresponding values

5-5-3 Route set evaluation

For the evaluation, we consider the criteria from section 4-3-2.

Computation time

The computation time of the route set generation algorithm depends on the number of Monte Carlo simulations x used for the non-deterministic part of the route set. The running time for $x = 50$ and 9 connections is around 3,5 hours for a single scenario (peak hour or non-peak hour) for a total of 43 days. The long computation is mainly caused by the fact that at every observation in time a new route set is generated. For the purpose of this research, the computation time can be considered long, but is not unacceptable as it has to run twice in total, for both scenarios. When a larger amount of *OD*-pairs should be considered, the computation time would become unacceptable and changes regarding the algorithm and the idea of route set regeneration per observation must be reconsidered.

Exclusion of irrelevant and erroneous routes

The route set generation excludes duplicate and circuitous routes. However, the route set generator does not always exclude irrelevant routes. A classic example is the ‘off-ramp-on-ramp’ situation, where a route exits the main road through an off-ramp just to enter the main road again through the corresponding on-ramp. A similar example is the entering and exiting of a parallel road. An illustration of the second example is provided in figure 5-5.

For the purpose of the research, this is obviously undesired, but is not of influence on the validity of presented results as the indicators do not distinguish between on-ramp or off-ramps and they are treated like any other alternative route. When considering the results for the



Figure 5-5: Example of irrelevant route (illustrated in green)

actual routes, it does become problematic and therefore it not possible to provide conclusions with regard to quality of case-specific routes. The results should therefore be treated separately from the actual representation in the network. If case-specific conclusion must be drawn, reconsideration of the generation procedure might be necessary as the irrelevant routes should in this case be removed from the set.

Variety of routes and route set size

In this thesis, the route set generator includes all levels of scale in the route set generation. The variety of routes is therefore considered sufficient, except for *OD*-pair #8. Apparently, no actual data has been measured in this area therefore leading to a route set consisting of 1 route, with no actual measurements. Consequently, this *OD*-pair is excluded for the remainder of this research. It must be noted that for #6 and #7 also a lack of data and variety can be observed, yet the extend thereof is less than with #8. Therefore, these pairs are preserved.

The sizes of the route sets change over time. With current model settings and depending on the *OD*-pair investigated, the dispersion in route set changes as is illustrated in figure 5-6. Note that in this case the peak hour scenario is depicted.

Figure 5-6 shows that the sizes of the route sets can vary significantly for some *OD*-pairs,

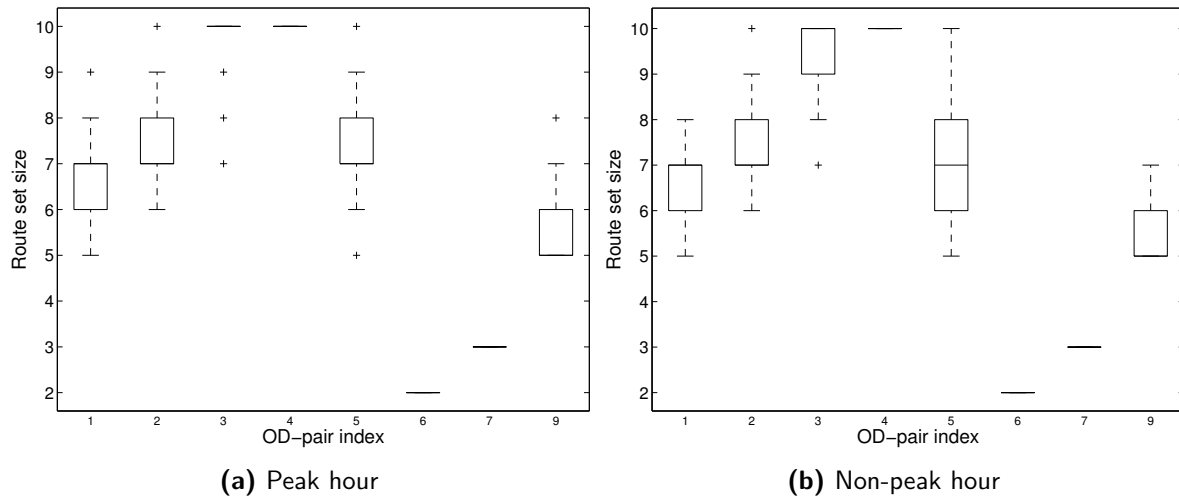


Figure 5-6: Dispersion of the route set size

while for other almost no variation is detected. Nevertheless, for all considered *OD*-pairs it can be determined that the majority of observations has a comparable route set size, with a few outliers that are either caused by an exceptional traffic state or by the stochastic element in the generation process. Appendix C shows the effect of the model parameters on the set size and set size dispersion.

Coverage

The coverage Ω of the generated route sets is conventionally determined by comparison with actual observed routes taken by travelers (see section 3-1). In this specific case, no such data is present and therefore the coverage of the route set is based on expert judgement at the discretion of the modeler. In this case, the coverage of the route set is considered sufficient for the purposes of this research. Again, in the same way as with the exclusion of irrelevant routes, it must be noted that when specific case related conclusions with regard to the actual routes are drawn, reconsideration of the generation procedure might be necessary in order to provide better representative results.

5-6 Route choice model estimation

During this case study, the route choice model serves a purpose and the estimation itself is not part of the main focus of the research. Given this and the fact that data containing actual observed routes taken (floating car data for example) is not present during the course of this research, the estimation of the model is based on values found in previous studies.

The formulation and estimation of the parameters of the components is based on Lam and Small (2001), Bekhor et al. (2006) and Bierlaire et al. (2006). As not every study held the same components, estimation of the complete function is based on expert judgment. Estimated values from literature are represented in table 5-6. Note that the values a and b are a representation of the mutual relationship between parameters that cannot be derived directly from literature.

β parameter	Value
ln(PS)	1
Mean	β_a^*
SD	$3.71 \cdot \beta_a^*$
Median	β_b^*
Perc90 minus median	$1.77 \cdot \beta_b^*$
Proportion highway	-2.2
Proportion urban roads	-4.4

Table 5-6: Parameter values for route choice modeling

Considering table 5-6, the utility functions can be rewritten as represented in equations (5-2) and (5-3).

$$U_{mean-variance,p} = \beta_a^* \left[\mu + f_\sigma \cdot \sigma_p \right] + \beta_c^* \left[\ln(PS_p) + f_{HW} \cdot \xi_{HW} + f_{urb} \cdot (1 - \xi_{HW}) \right] \quad (5-2)$$

$$U_{median-perc,p} = \beta_b^* \left[med + f_{perc90} \cdot \tau_{90\%-50\%} \right] + \beta_c^* \left[\ln(PS_p) + f_{HW} \cdot \xi_{HW} + f_{urb} \cdot (1 - \xi_{HW}) \right] \quad (5-3)$$

where the β^* values represent parts of the utility function that are dependent of each other and the different f_i values express the ratio within these dependent parts. At first glance, it can be determined that $\beta_c^* = \beta_{PS} = 1$ and the ratio values f are the remaining β parameters from table 5-6.

We can derive values for β_a^* and β_b^* , as represented in table 5-7. For the determination of these values and a sensitivity analysis, we refer to Appendix A.

β^* parameter	Value
a	-0.37
b	-0.37

Table 5-7: Parameter values for route choice modeling

For the representation of the route choice model, the median-percentile function is selected. The route choice model is applied at every observation t in interval T , thereby leading to a path set and its corresponding probabilities of selection per path at every step t in interval T . Aggregation is performed over the path set, leading to a single value per observation t , the aggregated travel time by route choice model. When performing this aggregation for every observation t , we can acquire the aggregated travel time distribution by route choice model. The aggregation of paths using their corresponding probabilities following from the route choice model can be performed discretely (all-or-nothing assignment for the route with the highest probability) or using the *scaled mean method*. A discrete selection is not a decent representation of the average ‘normal’ traveler, as routes with lower probabilities are excluded completely while a part of the travelers would select that route. Therefore, a weighted travel time based on the probabilities is selected. The scaled mean method basically comes down to the calculation method explained in equations 5-4 and 5-5.

First, for a single OD pair rs , we assume the travel time $\tau_{t,p}$ for all paths $p \in C^{rs}$ at a single observations $t \in T$ (5-4) and their respective probabilities (5-5).

$$\mathcal{T}_t = [\tau_{t,1}, \tau_{t,2}, \dots, \tau_{t,p}] \quad (5-4)$$

$$P_t = [p(t, 1), p(t, 2), \dots, p(t, p)] \quad (5-5)$$

From here, it is possible to acquire the aggregated travel time for the OD pair for observation t using the weighted travel times based on probabilities resulting from the route choice model.

$$\tau_{agg,t}^{RC} = \sum_{i=1}^p (\mathcal{T}_t \cdot P_{t,i}) \quad (5-6)$$

When considering all observations T , the previous is repeated per observation t ,

$$\mathcal{T}_{agg,T}^{RC} = [\tau_{agg,1}^{RC}, \tau_{agg,2}^{RC}, \dots, \tau_{agg,t}^{RC}] \quad (5-7)$$

thereby acquiring a distribution of aggregated paths for the route choice model scenario.

5-7 Implementation of connectivity indicator

The indicator is implemented for both scenarios as formulated in section 5-3, for a time interval during which it is peak hour on the network and for a time interval where this is not the case.

At every observation t , a trajectory is started, simulating a departure at that time in interval T and the corresponding connectivity value found by the indicator. For both scenarios, the connectivity indicator is implemented for 43 Tuesdays of which the values are averaged per observation t . The result is the course of the quality of the connection, set against the departure time of the trajectories. The averaged results are presented in figure 5-7. The dispersion of the indicator values over the days is represented in the standard deviation, illustrated in figure 5-8.

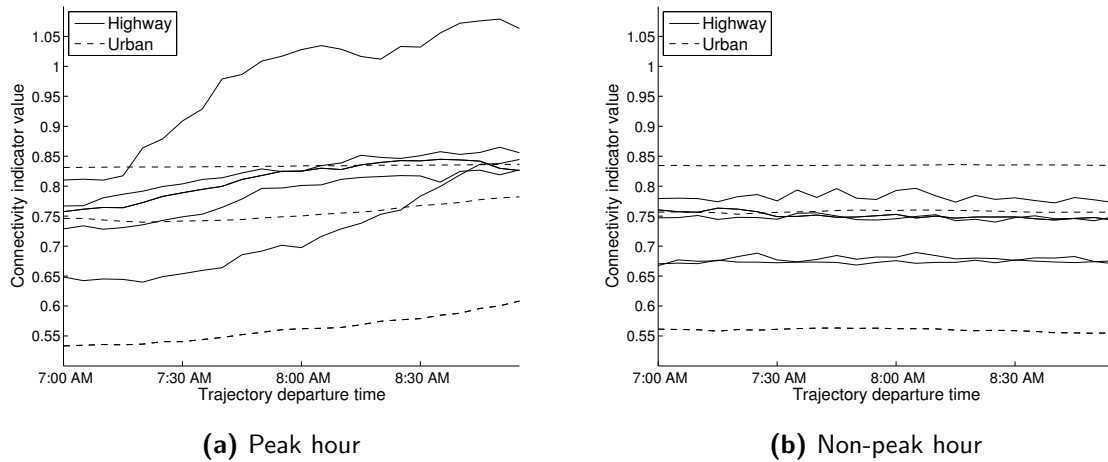


Figure 5-7: Averaged value of the connectivity indicator set against the departure

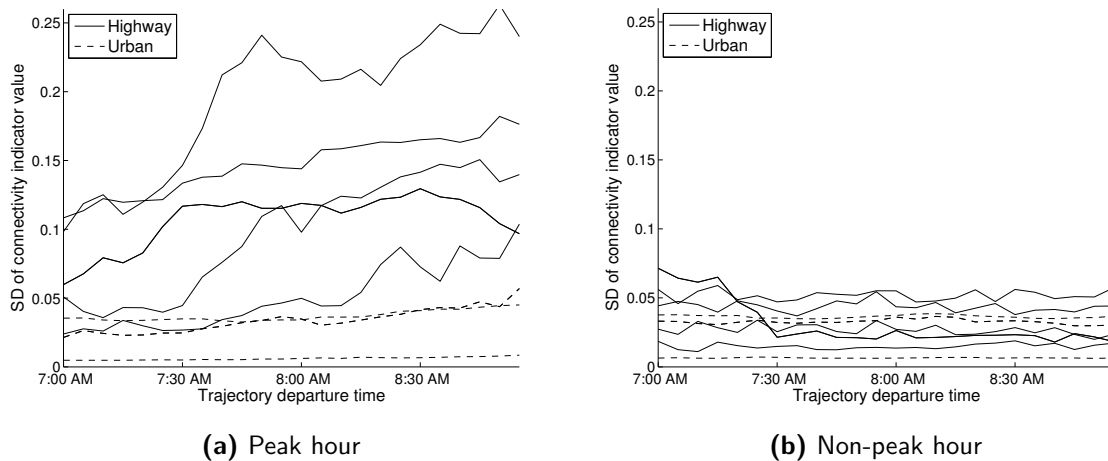


Figure 5-8: Standard deviation of the connectivity indicator value set against the departure

From these results, we can distinguish the difference between the two main time scenarios and the highway and urban roads.

<i>OD-pair index</i>	Value at 7h00AM	Value at 9h00AM	Relative change (%)
1	0.76	0.83	9.0
2	0.77	0.86	11.6
3	0.73	0.83	13.5
4	0.65	0.84	30.3
5	0.81	1.06	31.2
6	0.83	0.84	0.6
7	0.75	0.78	4.8
9	0.53	0.61	14.0
Average	0.73	0.83	14.4

Table 5-8: connectivity values for 7h00AM and 10h00AM and the relative change

<i>OD-pair index</i>	Value at 12h00PM	Value at 15h00PM	Relative change (%)
1	0.76	0.74	-2.2
2	0.67	0.68	0.8
3	0.74	0.75	0.3
4	0.67	0.67	0.5
5	0.78	0.77	-0.9
6	0.83	0.83	0.1
7	0.76	0.76	0.0
9	0.56	0.56	-1.0
Average	0.72	0.72	-0.3

Table 5-9: connectivity values for 12h00PM and 15h00PM and the relative change

Peak hour and non-peak hour interval

It can be expected that during the peak hour on the network, the usage of the network and the connections between *OD*-pairs is higher as during this period a large number of travelers use the network. It is therefore logical that because of this higher utilization, connections become more crowded, reaching maximum capacity and travel times on the routes within a connection go up. This is illustrated in the results presented in figure 5-7a, where a distinct rise of connectivity can be observed as the departure times within the peak hour interval progresses. At a time of 7h00AM, at the start of the peak hour, the quality of the connections is comparable with the value found outside of the peak hour. This can be said for both highway and urban connections. When departing at a time of 9h00AM, the indicator value shows significant increases in comparison with the value found at 7h00AM, while outside of the peak hour we do not observe this degradation of quality. Table 5-8 and 5-9 show the relative increase of the connectivity value per *OD*-pair when departing at 9h00AM instead of 7h00AM for both peak hour and non-peak hour respectively.

From table 5-8, we can determine that for connections #4 and #5 the degradation is a third of the original quality value. Other connections show a decrease in quality of around 10%, with the notable exception of connection 6. Considering all connections, an average quality degradation of around 14% is observed. It must be noted that standard deviation of the connectivity value over the measures days is significant (occasionally over 30% of the average

value) and that although the average shows a steady rise, the standard deviation illustrates that the quality can be significantly different over the days. This is in line expectation, as not all peak hours are of the same magnitude and may be influenced by non-recurrent events, such as bad weather or an accident. Despite the dispersion of connectivity over the days, it can be said that the peak hour has significant effect on the quality of the connection in the case study area.

Table 5-9 and figure 5-8b show that in the time interval observed outside the peak hour, the quality of the connections remains stable. This is in line with the expectation; it can be said that during this period, the quality of the connections is less dependent on the travel time dispersion and more on the availability of alternative routes. During this period the demand does not recurrently exceed road capacity, thereby having little differences in travel time dispersion over the interval. During this time it is assumed that the quality of the connections is optimal, thus connectivity is maximized. Here the differences in quality in freeflow conditions can be observed. When considering the rewritten definition of the connectivity indicator, depicted in (5-8), the distinction can be made between the part dependent on the dispersion and the part dependent on the number of alternatives in the route set.

$$I_t^{conn} = \underbrace{\frac{\Delta\bar{\tau}_t}{\tau_{ff}^b} + \frac{1}{\phi \tau_{ff}^b} \ln \left[\frac{\sum_{p \in \mathcal{C}^{rs}} \exp(\phi \cdot (\Delta\tau_t - \Delta\bar{\tau}_t))}{n} \right]}_{\text{Dispersion}} + \underbrace{\frac{1}{\phi \tau_{ff}^b} \ln(n) + 1}_{\text{\#alternatives}} \quad (5-8)$$

In figure 5-7b, several connections have a similar quality score, however it is not clear based on what properties this score is given. Figure 5-9 shows the relative influence of the part of the indicator dependent on the number of alternatives on the total value of the connectivity indicator. As this is a relative influence, per indicator multiple outcomes are possible dependent on the relation between dispersion and the number of alternatives.⁵

This figure shows that connections with different values for the indicator can have the same ratio, as mentioned earlier. On the other hand, the figure shows that connections with a similar indicator value can have different ratios. From this it can be determined that the indicator value alone might not be sufficient and the addition of the ratio between the number of alternatives and dispersion is necessary in order to indicate what the makeup of the indicator value is.

⁵For example: the ratio 1:1 is the same as 2:2, yet the sum is different. In this case this dependent on the ratio dispersion/#alternatives.

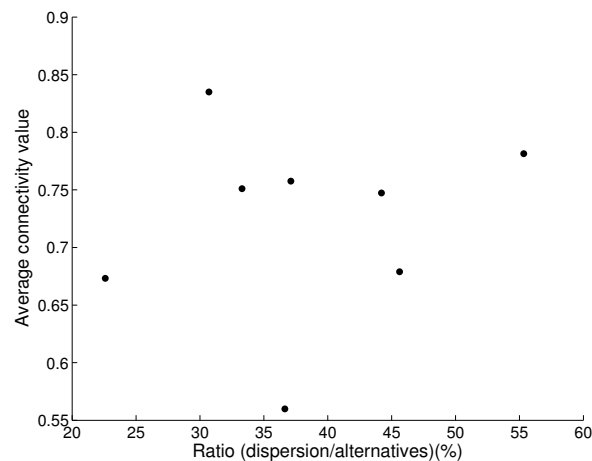


Figure 5-9: Relative indication of the influence of the number of alternatives on the connectivity indicator

Highway and urban connections

Considering figures 5-7 and 5-8, it can be determined that the quality of highway connections shows greater degradation in comparison to the urban connections in the peak hour interval. This can also be derived from the results in tables 5-8 and 5-9, where the relative connectivity in the peak hour is larger for the highway connections. Outside the peak hour, the behavior of the quality of the connections shows similar behavior. Furthermore, it can be said that the highway connection shows larger dispersion of degradation over the observed days, while the degradation increase of urban connections is relatively stable. When comparing the quality of the connections mutually under normal circumstances (no peak hour), it can be said that the actual quality determined from the connectivity value shows no obvious relation to the type of connection as both highway have varying scores. It can be said, however, that the quality values of the highway connections less spread than the values of the urban connections, where the scores differ significantly. For example, when contemplating table 5-9, it can be determined that the difference in quality between #6 and #9 differs more than 60%, suggesting large differences between these two urban connections.

Based on these results one might say that the quality of highway connection is less stable and more sensitive to degradation. However, the coverage of data on the lower network levels and thus on the urban connections, is less than on higher network levels such as highways. When data is missing, freeflow times are assumed in order to prevent data gaps. The fact that data gaps are compensated for with freeflow travel times may also be the cause of the higher stability of urban connections.

5-8 Analysis of perceived connection reliability

In this section an analysis of the perceived reliability of the connections is provided based on the performance indicators selected in chapter 4. The travel time distributions are aggregated in accordance with section 4-3. This section consists of:

1. The analysis of the difference between the reference distributions (base route and route choice modeling) and the distribution resulting from implementation of a fastest path algorithm. This is done for peak hour and non-peak hour scenario.
2. The analysis of the effect of the departure time in the peak hour and the improvement that can be gained by having a variable departure time within an interval. This is investigated for interval size 15 and 25 minutes.

5-8-1 Travel time reliability and implementation of the fastest path algorithm.

In this subsection, we compare the travel time distributions generated as reference distributions (no information or base route and the average traveler) with the distribution generated by the implementation of a fastest path algorithm in order to determine what perceived reliability could be gained when a traveler is well informed of what is the fastest route at that time. This is done for every investigated *OD*-pair (with the notable exception of #8) with a concise summary of the results observed, followed by a general analysis of the results regarding the influence of peak hour and the difference between urban and highway connections.

Note that the axis are variable in values and size; this is done in order to preserve the illustrative effect of the differences between the distributions. The sizes of the bars are therefore not mutually comparable.

In this subsection, the relative difference between scenarios is represented.

For *OD*-pair #1, the travel time distributions are illustrated for peak hour and non-peak hour in figures 5-10. Tables 5-10 and 5-11 represent the relative difference between the distribution for peak hour and non-peak hour. The base route distribution is set as the reference distribution. Note that positive relative values represent an improvement, while negative values represent a decline. Values are rounded to integers.

From figures 5-10 it can be observed that all distributions are significantly better outside of peak hour than during peak hour, which is a logical observation. It is, however, interesting to note that although all distributions are placed more to the left, even outside the peak hour large outliers can be observed. These are likely to be caused by non-recurrent events as the frequency is very low. Furthermore, it can be noted that the base route distribution is very similar to that of the fastest path algorithm. This is in line with the expectation that the base

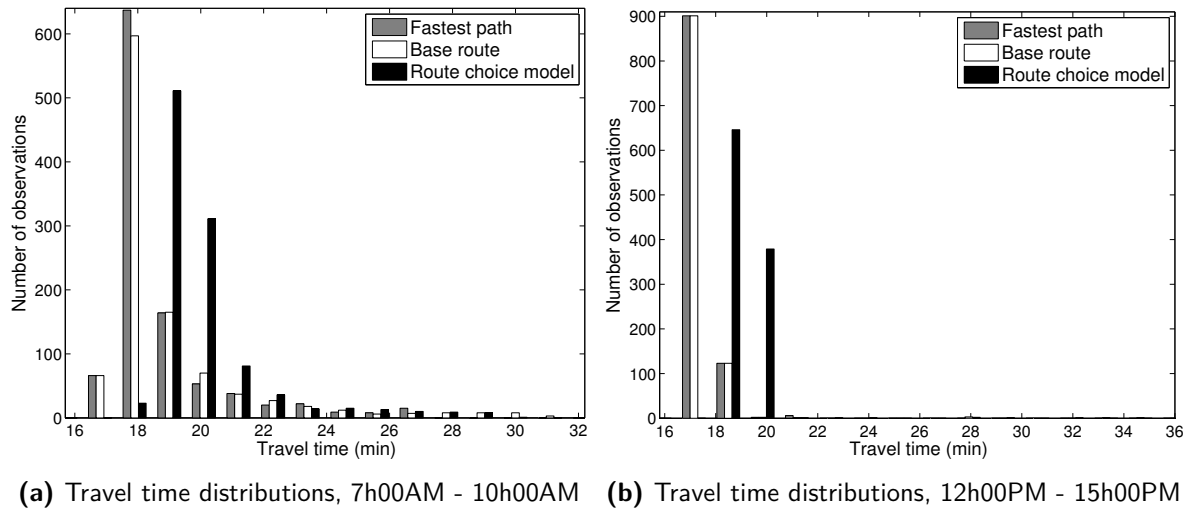


Figure 5-10: Travel time distributions for *OD*-index #1

Performance indicator	Route choice model (%)	Fastest path (%)
Average	-6	1
Standard deviation	23	24
Buffer index	40	19
MAD	2	22
Delay ind.	-61	14

Table 5-10: Performance indicator values relative to the base route values for *OD*-pair #1 between 7h00AM and 10h00AM

Performance indicator	Route choice model (%)	Fastest path (%)
Average	-8	0
Standard deviation	26	63
Buffer index	-13	0
MAD	2	25
Delay ind.	-207	7

Table 5-11: Performance indicator values relative to the base route values for *OD*-pair #1 between 12h00PM and 15h00PM

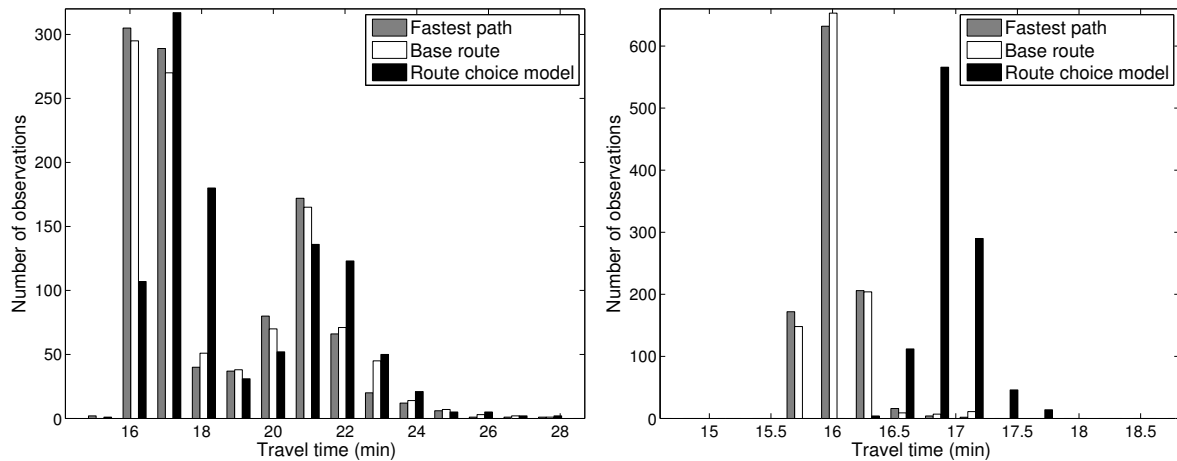
route is usually the fastest route. For this *OD*-pair, the base route remains the fastest in the majority of observations, even though it is peak hour. Yet, table 5-10 shows that, although this is the case, still a significant improvement in reliability can be observed when a fastest path algorithm is used. Outside of the peak hour the difference is much less.

It can also be determined that in this case the best reference distribution is the base route when considering travel time. The route choice model shows with regard to reliability in the peak hour a slight improvement, with the exception of the delay. It can be said that for this situation always following the fastest freeflow route would provide with decent perceived travel time reliability.

Furthermore, this *OD*-pair is a good example why the average is not very representative

when considering reliability, as it barely changes while reliability indicators show significant improvements.

For *OD*-pair #2, the travel time distributions are illustrated for peak hour and non-peak hour in figures 5-11. Tables 5-12 and 5-13 represent the relative difference between the distribution for peak hour and non-peak hour.



(a) Travel time distributions, 7h00AM - 10h00AM (b) Travel time distributions, 12h00PM - 15h00PM

Figure 5-11: Travel time distributions for *OD*-index #2

Performance indicator	Route choice model (%)	Fastest path (%)
Average	-3	1
Standard deviation	5	5
Buffer index	9	3
MAD	5	8
Delay ind.	-18	6

Table 5-12: Performance indicator values relative to the base route values for *OD*-pair #2 between 7h00AM and 10h00AM

Performance indicator	Route choice model (%)	Fastest path (%)
Average	-6	0
Standard deviation	17	10
Buffer index	45	0
MAD	16	7
Delay ind.	-304	5

Table 5-13: Performance indicator values relative to the base route values for *OD*-pair #2 between 12h00PM and 15h00PM

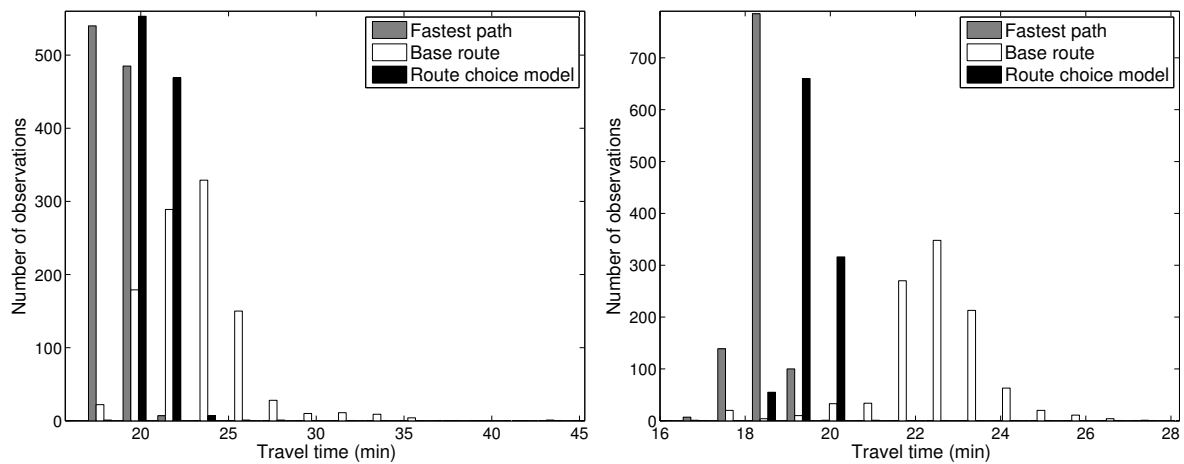
It can be observed from figures 5-11 that during peak hours, large delays are suffered on this connection. Outliers in the peak hour go up to 28 minutes, while outside the peak hour no such outliers are present. The locations of the peaks are at about the same locations for all distributions, although the number of observation is much lower, indicating a larger spread of the travel times in the peak hour compared to outside of the peak hour. Considering this

fact, it is interesting to note that the implementation of the fastest path algorithm for this connection generates limited improvements in reliability, indicating that despite the delays on the base route, having alternatives provides only a modest improvement in reliability and a limited 6% decrease in suffered delay.

The route choice model distribution provides improvements in reliability but a decrease in average travel time and suffered delay compared to the base route. Within the peak hour, the improvements in reliability and the decline in average travel time and delay may balance out. Outside the peak hour, the delay suffered is over 300% more so here it would be better to follow the base route.

Comparing with the *OD*-pair #1, the behavior of this connection is similar with a base route that is fastest the majority of the observation despite the delay on this route. The fastest path algorithm again shows improvement with regard to perceived reliability, while the average travel time remains (almost) the same.

For *OD*-pair #3, the travel time distributions are illustrated for peak hour and non-peak hour in figures 5-12. Tables 5-14 and 5-15 represent the relative difference between the distribution for peak hour and non-peak hour.



(a) Travel time distributions, 7h00AM - 10h00AM (b) Travel time distributions, 12h00PM - 15h00PM

Figure 5-12: Travel time distributions for *OD*-index #3

Performance indicator	Route choice model (%)	Fastest path (%)
Average	10	19
Standard deviation	79	77
Buffer index	74	64
MAD	83	82
Delay ind.	37	69

Table 5-14: Performance indicator values relative to the base route values for *OD*-pair #3 between 7h00AM and 10h00AM

Performance indicator	Route choice model (%)	Fastest path (%)
Average	13	18
Standard deviation	74	71
Buffer index	70	72
MAD	70	68
Delay ind.	51	70

Table 5-15: Performance indicator values relative to the base route values for *OD*-pair #3 between 12h00PM and 15h00PM

The most notable observation for this connection is the fact that the base route distribution is significantly worse than the both the other distributions, with huge differences in average, reliability and delay. In case of peak hour, this can be explained by the fact that during this period this is particular route is congested, while alternatives are not. However, the same order of improvement can be noted for the situation outside of the peak hour. This either suggest that the route is congested during the entire day, or that a flaw in the data caused the freeflow travel time of that route to be too low in comparison with actual measurements. The last seems to be most likely, as no route is almost always congested (at least not in this case study area). It means that either the calculated freeflow travel time of the route is erroneous, or the measurements are incorrect. Whatever the cause, the representativeness of this connection can be considered compromised.

For *OD*-pair #4, the travel time distributions are illustrated for peak hour and non-peak hour in figures 5-13. Tables 5-16 and 5-17 represent the relative difference between the distribution for peak hour and non-peak hour.

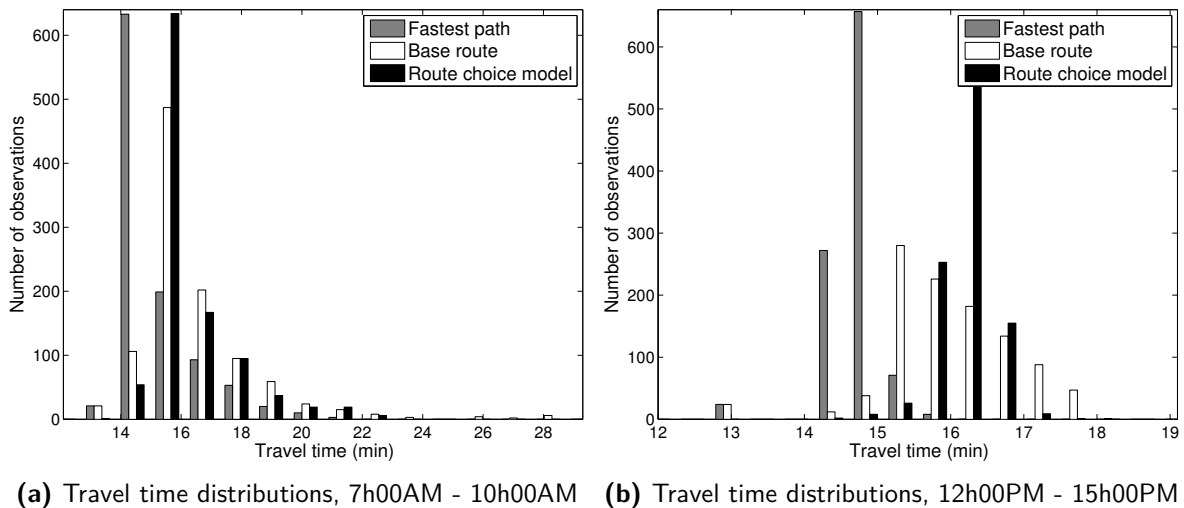


Figure 5-13: Travel time distributions for *OD*-index #4

From tables 5-16 and 5-17 it can be determined that the relative improvements of both distributions in comparison with base route are large. During peak hour, the delay suffered is decreased for a large percentage by using the fastest path, while outside the peak hour the

Performance indicator	Route choice model (%)	Fastest path (%)
Average	1	7
Standard deviation	29	39
Buffer index	17	19
MAD	47	73
Delay ind.	69	35

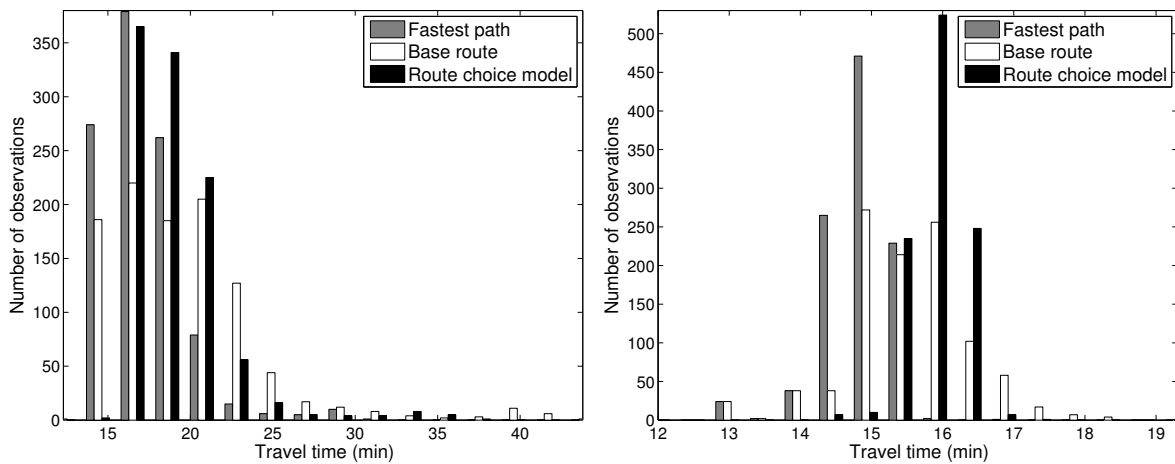
Table 5-16: Performance indicator values relative to the base route values for *OD*-pair #4 between 7h00AM and 10h00AM

Performance indicator	Route choice model (%)	Fastest path (%)
Average	-1	8
Standard deviation	60	62
Buffer index	67	73
MAD	62	73
Delay ind.	-8	42

Table 5-17: Performance indicator values relative to the base route values for *OD*-pair #4 between 12h00PM and 15h00PM

most is gained in reliability improvements. For this connection, the route choice model shows also improvements over a single route connection.

For *OD*-pair #5, the travel time distributions are illustrated for peak hour and non-peak hour in figures 5-14. Tables 5-18 and 5-19 represent the relative difference between the distribution for peak hour and non-peak hour.



(a) Travel time distributions, 7h00AM - 10h00AM (b) Travel time distributions, 12h00PM - 15h00PM

Figure 5-14: Travel time distributions for *OD*-index #5

The relative results of the performance indicators are similar to those of *OD*-pair #4, where both the route choice model and the fastest route perform much better in reliability and delay in the peak hour. Outside the peak hour, the route choice model distribution is much more reliable, but performs worse for the average travel time and the delay. Furthermore, we can observe some extreme outliers for this connection for the base route and route choice model,

Performance indicator	Route choice model (%)	Fastest path (%)
Average	2	12
Standard deviation	39	48
Buffer index	43	39
MAD	45	46
Delay ind.	76	37

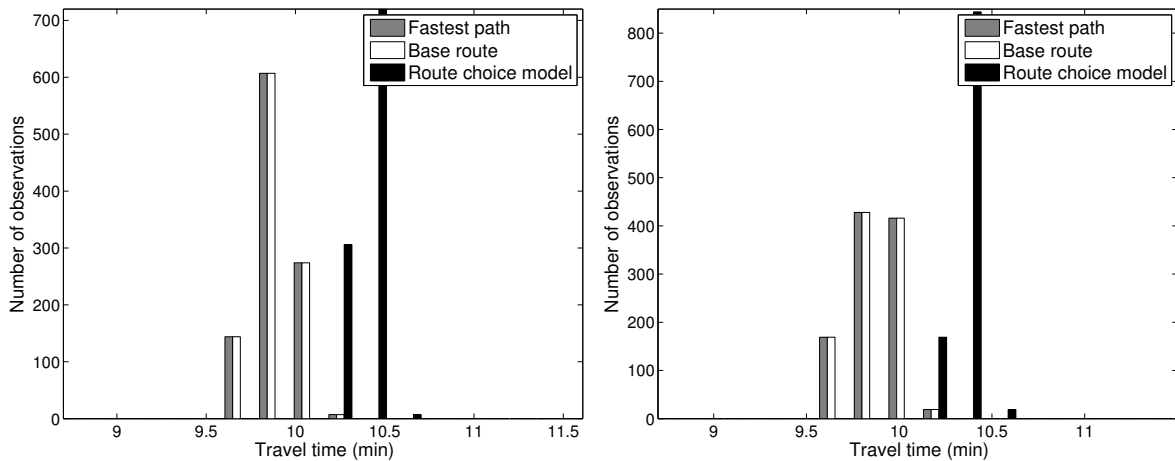
Table 5-18: Performance indicator values relative to the base route values for *OD*-pair #5 between 7h00AM and 10h00AM

Performance indicator	Route choice model (%)	Fastest path (%)
Average	-3	4
Standard deviation	57	45
Buffer index	57	58
MAD	56	45
Delay ind.	-18	30

Table 5-19: Performance indicator values relative to the base route values for *OD*-pair #5 between 12h00PM and 15h00PM

with travel times over the 40 minutes in the peak hour. Comparing this to the majority of the observations, which are around 17 minutes to 22 minutes, these outliers are considerable. It is likely that the large improvements in reliability are caused by these outliers, which are not present in the fastest route distribution and in less considerable degree in the route choice model distribution.

For *OD*-pair #6, the travel time distributions are illustrated for peak hour and non-peak hour in figures 5-15. Tables 5-20 and 5-21 represent the relative difference between the distribution for peak hour and non-peak hour.



(a) Travel time distributions, 7h00AM - 10h00AM (b) Travel time distributions, 12h00PM - 15h00PM

Figure 5-15: Travel time distributions for *OD*-index #6

The base route is for every observation equal to the fastest route. The route choice model provides better reliability results, although this inherent to the fact this method utilizes the

Performance indicator	Route choice model (%)	Fastest path (%)
Average	-5	0
Standard deviation	44	0
Buffer index	46	0
MAD	44	0
Delay ind.	-262	0

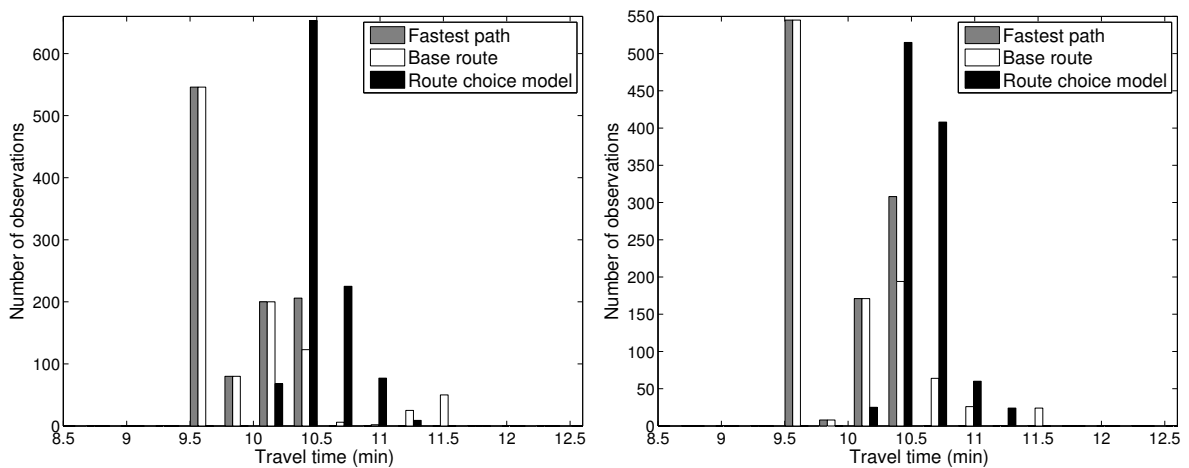
Table 5-20: Performance indicator values relative to the base route values for *OD*-pair #6 between 7h00AM and 10h00AM

Performance indicator	Route choice model (%)	Fastest path (%)
Average	-5	0
Standard deviation	44	0
Buffer index	47	0
MAD	44	0
Delay ind.	-232	0

Table 5-21: Performance indicator values relative to the base route values for *OD*-pair #6 between 12h00PM and 15h00PM

weighted mean. With respect to the average travel time and the delay suffered, the route choice model distributions shows a large decline. For this connection, using the base route provides with the best results.

For *OD*-pair #7, the travel time distributions are illustrated for peak hour and non-peak hour in figures 5-16. Tables 5-22 and 5-23 represent the relative difference between the distribution for peak hour and non-peak hour.



(a) Travel time distributions, 7h00AM - 10h00AM **(b)** Travel time distributions, 12h00PM - 15h00PM

Figure 5-16: Travel time distributions for *OD*-index #7

Relative improvement for this connection when using the fastest path algorithm is similar during peak hour and non-peak hour. This can also be observed in figures 5-16, where the distributions for the base route and fastest path are equal during normal lower travel times but are not when this increases beyond a certain travel time on the base route. It can be

Performance indicator	Route choice model (%)	Fastest path (%)
Average	-6	1
Standard deviation	62	29
Buffer index	63	0
MAD	41	0
Delay ind.	-136	16

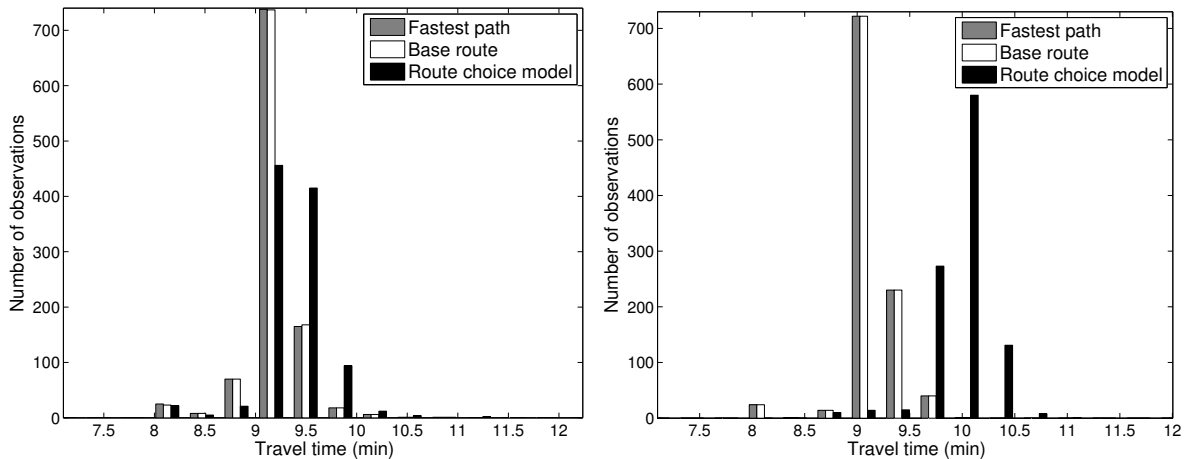
Table 5-22: Performance indicator values relative to the base route values for *OD*-pair #7 between 7h00AM and 10h00AM

Performance indicator	Route choice model (%)	Fastest path (%)
Average	-6	0
Standard deviation	60	19.5
Buffer index	67	11
MAD	60	11
Delay ind.	-138	11

Table 5-23: Performance indicator values relative to the base route values for *OD*-pair #7 between 12h00PM and 15h00PM

noted that for this connection the base route is a good option and an improvement is only possible for the outliers, which are only a few minutes slower. The route choice model again shows the by now familiar pattern of higher reliability and much lower scores in average travel time and delay.

For *OD*-pair #9, the travel time distributions are illustrated for peak hour and non-peak hour in figures 5-17. Tables 5-24 and 5-25 represent the relative difference between the distribution for peak hour and non-peak hour.



(a) Travel time distributions, 7h00AM - 10h00AM **(b)** Travel time distributions, 12h00PM - 15h00PM

Figure 5-17: Travel time distributions for *OD*-index #9

The results for this connection are almost the same as for *OD*-pair #7, with the exception that there is a very small difference between the base route distribution and the fastest route distribution. This difference can be considered negligible as the effect on the performance

Performance indicator	Route choice model (%)	Fastest path (%)
Average	-2	0
Standard deviation	-13	-1
Buffer index	-29	0
MAD	-67	0
Delay ind.	-15	0

Table 5-24: Performance indicator values relative to the base route values for *OD*-pair #9 between 7h00AM and 10h00AM

Performance indicator	Route choice model (%)	Fastest path (%)
Average	-8	0
Standard deviation	-8	0
Buffer index	-8	0
MAD	-14	0
Delay ind.	-72	0

Table 5-25: Performance indicator values relative to the base route values for *OD*-pair #9 between 12h00PM and 15h00PM

indicators for both peak and non-peak scenarios is almost none. Note that for the peak hour the fastest route distribution appears to score slightly worse than the base route, however, this is the result of the rounding of the percentages.

Summary

The results can be summarized by the following statements:

1. With regard to the base route, it is expected that because it is the fastest freeflow route it should be the fastest under normal condition. We distinguish the *OD*-pairs where this indeed the case (1,2,5,6,7) and the *OD*-pairs where despite this fact the base route is rarely the fastest (3,4,9). The last is contradictory to expectation, as under normal conditions no delay is expected and thus freeflow travel times should be observed.
2. The route choice model shows occasional improvements with regard to travel time reliability, but has a persistent higher average and delay. This is in line with expectation as the route choice process is based on more properties except travel time.
3. The fastest path algorithm represents a traveler that is fully informed about what routes are the fastest at a particular time. The results show a persistent improvement when comparing to the reference distributions. With the exception of connection #6, where the base route is always the fastest as well, large improvements with regard to reliability and delay can be achieved when fully informing a traveler. Note that the improvement of the average is much smaller.

5-8-2 Variable departure times

The perception of travel time reliability on a connection depends on the time of departure, as the state of the network changes over time. By changing departure time, it may be possible to encounter a better situation on the network and thus a lower travel time. However, it is not by definition possible to alter departure time as travelers have a certain destination at which they are required to arrive in time. Especially work-related traffic has this requirement and it is because of this peak hours exist as all work-related traffic is on the road at the same time. When we consider such a traveler, it can be said that in order to arrive in time this traveler has a certain departure time. As his required arrival time is static, the departure time is static as well.

In this subsection, we determine the perception of reliability for different static departure times. Furthermore, the possible improvements in reliability gained by having a variable departure are investigated. We consider the static departure times 7h00AM, 8h00AM and 8h30AM. The inclusion of variability in the departure times is done by investigating a certain interval around the static departure time and whether a departure time within this interval shows improvement over the initial static departure time. Here we consider two interval lengths: 15 and 25 minutes.

With regard to route choice, we assume the traveler is fully informed (which is logical as he familiar with the connection as he uses it every workday), meaning that the fastest route is selected for the static departure times. Furthermore, we assume that the traveler is fully informed of the travel times within the interval around the static departure time, leading to the selection of the fastest route at the optimal departure time within the interval.

This is done for a total of 43 days, thereby acquiring (1) the travel time distributions for the static and variable departure times and the reliability performance and (2) the percentage of delay prevented by having a variable departure time. For this situation we consider only the peak hour as this is most relevant. Results are presented below.

Reliability

The travel time distributions for the static departure times and the variable departure times are created and analyzed in a similar fashion as with the overall perceived reliability in subsection 5-8-1. The same reliability performance indicators are used. Figure 5-18 is a representation of the travel time distributions as created for *OD*-pair #1, which functions as an exemplary illustration.

These figures show that as the peak hour progresses, the reliability of the distributions declines. Furthermore, it can be noticed that the distributions of the variable departure times

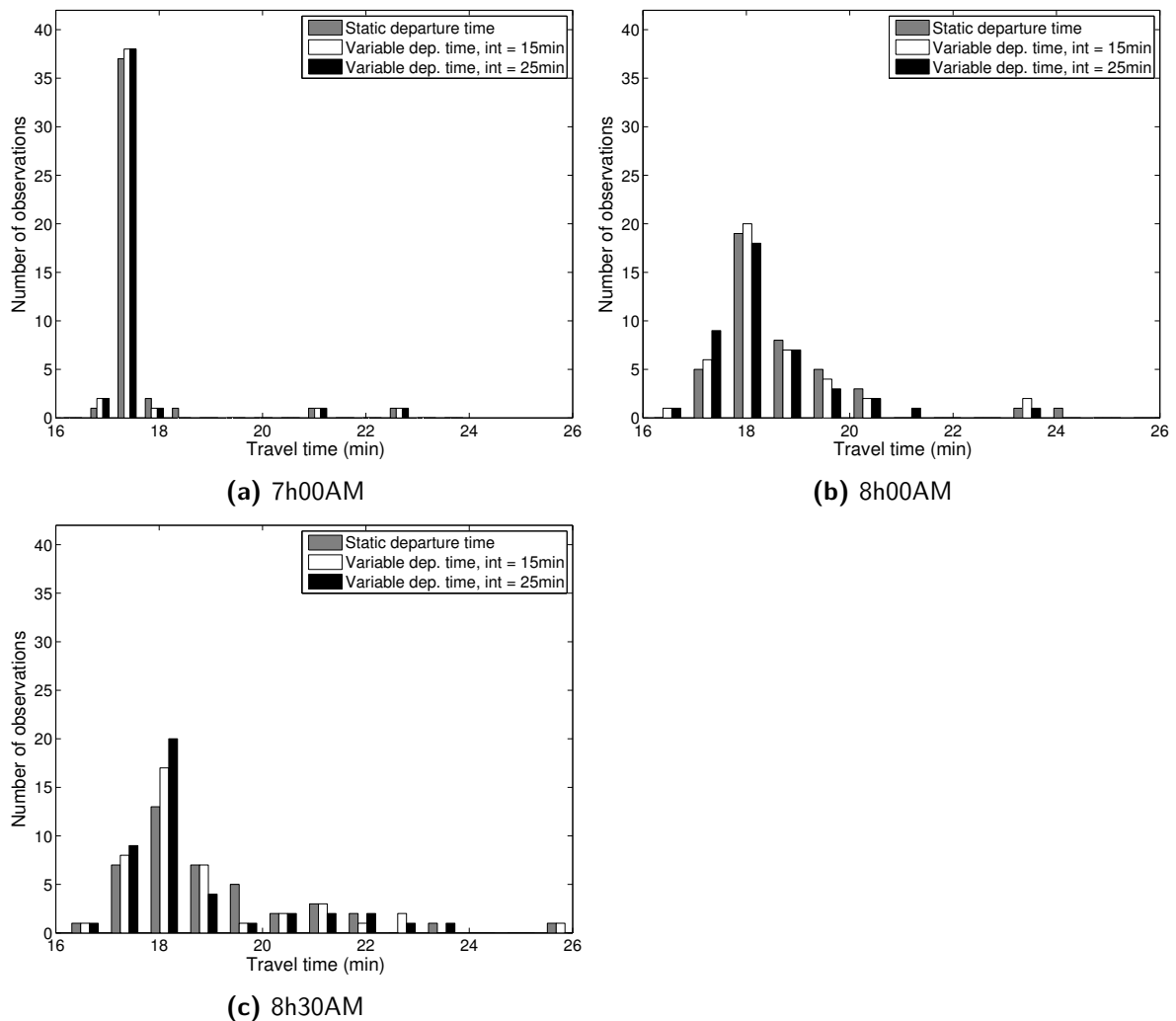


Figure 5-18: Travel time distributions for *OD*-index #1 for different departure times

are moved slightly to the left, indicating improvement over the static departure time distribution. Similar figures can be made for the remaining *OD*-pairs, yet for the purpose of illustration an exemplary *OD*-pair is deemed sufficient.

Tables 5-26 through 5-33 show the results of the reliability indicators for the *OD*-pairs. These tables indicate the relative change of the distributions of the variable departure times compared to the static departure time distributions. Note that the percentages are rounded to integers.

Based on these results, we can state the following regarding travel time reliability:

1. Most indicators show a consistent improvement of the distribution for a variable departure time in comparison with a static departure time. This greatly differs between the *OD*-pairs and ranges from 0% to 50%.

Performance indicator	7h00AM, 15 minutes (%)	7h00AM, 25 minutes (%)	8h00AM, 15 minutes (%)	8h00AM, 25 minutes (%)	8h30AM, 15 minutes (%)	8h30AM, 25 minutes (%)
Average	0	0	1	2	2	2
Standard deviation	-1	-1	3	10	13	24
Buffer index	50	50	11	11	-4	-4
MAD	0	0	5	13	11	21
Delay ind.	4	4	11	16	14	22

Table 5-26: Relative performance of the variable departure times compared to the corresponding static travel times for *OD*-pair #1

Performance indicator	7h00AM, 15 minutes (%)	7h00AM, 25 minutes (%)	8h00AM, 15 minutes (%)	8h00AM, 25 minutes (%)	8h30AM, 15 minutes (%)	8h30AM, 25 minutes (%)
Average	0	1	1	1	1	2
Standard deviation	2	6	3	6	2	3
Buffer index	-2	10	-8	-9	-8	-8
MAD	2	5	3	6	2	4
Delay ind.	4	6	6	9	6	13

Table 5-27: Relative performance of the variable departure times compared to the corresponding static travel times for *OD*-pair #2

Performance indicator	7h00AM, 15 minutes (%)	7h00AM, 25 minutes (%)	8h00AM, 15 minutes (%)	8h00AM, 25 minutes (%)	8h30AM, 15 minutes (%)	8h30AM, 25 minutes (%)
Average	0	1	1	2	2	3
Standard deviation	1	-9	12	23	31	45
Buffer index	-1	-1	-19	-30	48	48
MAD	5	2	15	25	35	43
Delay ind.	6	8	11	16	19	26

Table 5-28: Relative performance of the variable departure times compared to the corresponding static travel times for *OD*-pair #3

Performance indicator	7h00AM, 15 minutes (%)	7h00AM, 25 minutes (%)	8h00AM, 15 minutes (%)	8h00AM, 25 minutes (%)	8h30AM, 15 minutes (%)	8h30AM, 25 minutes (%)
Average	0	0	1	1	1	2
Standard deviation	4	4	12	18	18	27
Buffer index	55	55	-8	-24	30	30
MAD	5	5	16	22	21	31
Delay ind.	2	3	4	5	8	11

Table 5-29: Relative performance of the variable departure times compared to the corresponding static travel times for *OD*-pair #4

2. The Buffer time Index shows great fluctuations, even within connection. Furthermore are the results often in conflict with the other performance indicators and in case of

Performance indicator	7h00AM, 15 minutes (%)	7h00AM, 25 minutes (%)	8h00AM, 15 minutes (%)	8h00AM, 25 minutes (%)	8h30AM, 15 minutes (%)	8h30AM, 25 minutes (%)
Average	1	1	5	7	3	4
Standard deviation	0	22	18	20	9	13
Buffer index	6	6	-34	-60	44	44
MAD	6	15	30	33	21	26
Delay ind.	7	11	20	26	14	18

Table 5-30: Relative performance of the variable departure times compared to the corresponding static travel times for *OD*-pair #5

Performance indicator	7h00AM, 15 minutes (%)	7h00AM, 25 minutes (%)	8h00AM, 15 minutes (%)	8h00AM, 25 minutes (%)	8h30AM, 15 minutes (%)	8h30AM, 25 minutes (%)
Average	0	0	0	0	0	0
Standard deviation	0	1	1	2	1	2
Buffer index	-	-	0	0	0	0
MAD	0	1	-3	-4	3	6
Delay ind.	0	5	5	7	3	4

Table 5-31: Relative performance of the variable departure times compared to the corresponding static travel times for *OD*-pair #6

Performance indicator	7h00AM, 15 minutes (%)	7h00AM, 25 minutes (%)	8h00AM, 15 minutes (%)	8h00AM, 25 minutes (%)	8h30AM, 15 minutes (%)	8h30AM, 25 minutes (%)
Average	0	0	0	0	0	2
Standard deviation	3	3	0	0	2	2
Buffer index	0	0	0	0	0	0
MAD	3	3	-1	-1	2	2
Delay ind.	4	4	1	1	2	2

Table 5-32: Relative performance of the variable departure times compared to the corresponding static travel times for *OD*-pair #7

Performance indicator	7h00AM, 15 minutes (%)	7h00AM, 25 minutes (%)	8h00AM, 15 minutes (%)	8h00AM, 25 minutes (%)	8h30AM, 15 minutes (%)	8h30AM, 25 minutes (%)
Average	0	0	1	1	0	1
Standard deviation	3	1	26	26	1	-30
Buffer index	40	40	-50	1	0	0
MAD	5	0	19	19	2	-24
Delay ind.	1	2	6	7	1	6

Table 5-33: Relative performance of the variable departure times compared to the corresponding static travel times for *OD*-pair #9

connection #6 the Buffer time Index was 0 at 7h00AM, thereby making a relative comparison impossible. For the remainder of this analysis, the Buffer time Index is

considered with reservations.

3. The improvements are most notable for the highway connections.
4. The improvements are larger for a larger interval around the static departure time. This is in line with expectation since more departure times are considered and thus the chances of having a better option increases.
5. The improvements increase as the peak hour progresses for most *OD*-pairs, meaning that improvements are more notable for 8h30AM and from there descending to 7h00AM, where the improvements are less significant. For other *OD*-pairs, the peak of improvements can be found at 8h00AM, suggesting that the peak hour is not for every connection at its maximum at the same time in the observed interval of the day.

Delay

The delays suffered can be aggregated over the number of observed days, in this case 43. From tables 5-26 through 5-33 it can be determined that the average travel time and delay indicator show consistent improvement, suggesting variable travel times can decrease the suffered delay of the traveler. The improvements in suffered average delay over the 43 days are presented in figure 5-19, normalized by the average value of the static departure time distribution in the left column and normalized by the freeflow reference in the right column.

Based on figure 5-19, we state the following:

1. For the 7h00AM situation, the effect of variable departure time is very small, with only connection #5 surpassing the 1% improvement with a 25 minutes interval. For this departure time it can be said that the effect is minimal.
2. For the 8h00Am situation, the improvement in suffered delay is significant for the highway connections and urban connection #9. Connection #5 stands out with large improvement around 5% (15 minutes interval) and 7% (25 minutes interval).
3. The 8h30AM situation also shows significant improvement. It is interesting to observe that the merits of having variable travel times are for the first four connections, have increased in comparison with the 8h00AM situation, while connection #5 and #9 show a decrease in profit in comparison. This is line with the observation made regarding reliability where it is noted that the peak hour is not at its maximum for all connections at the same time.
4. The urban connections show very little improvement, with connection #9 being the only connection with notable improvement. From this it appears that the having a variable departure time is of most use on highway connections.

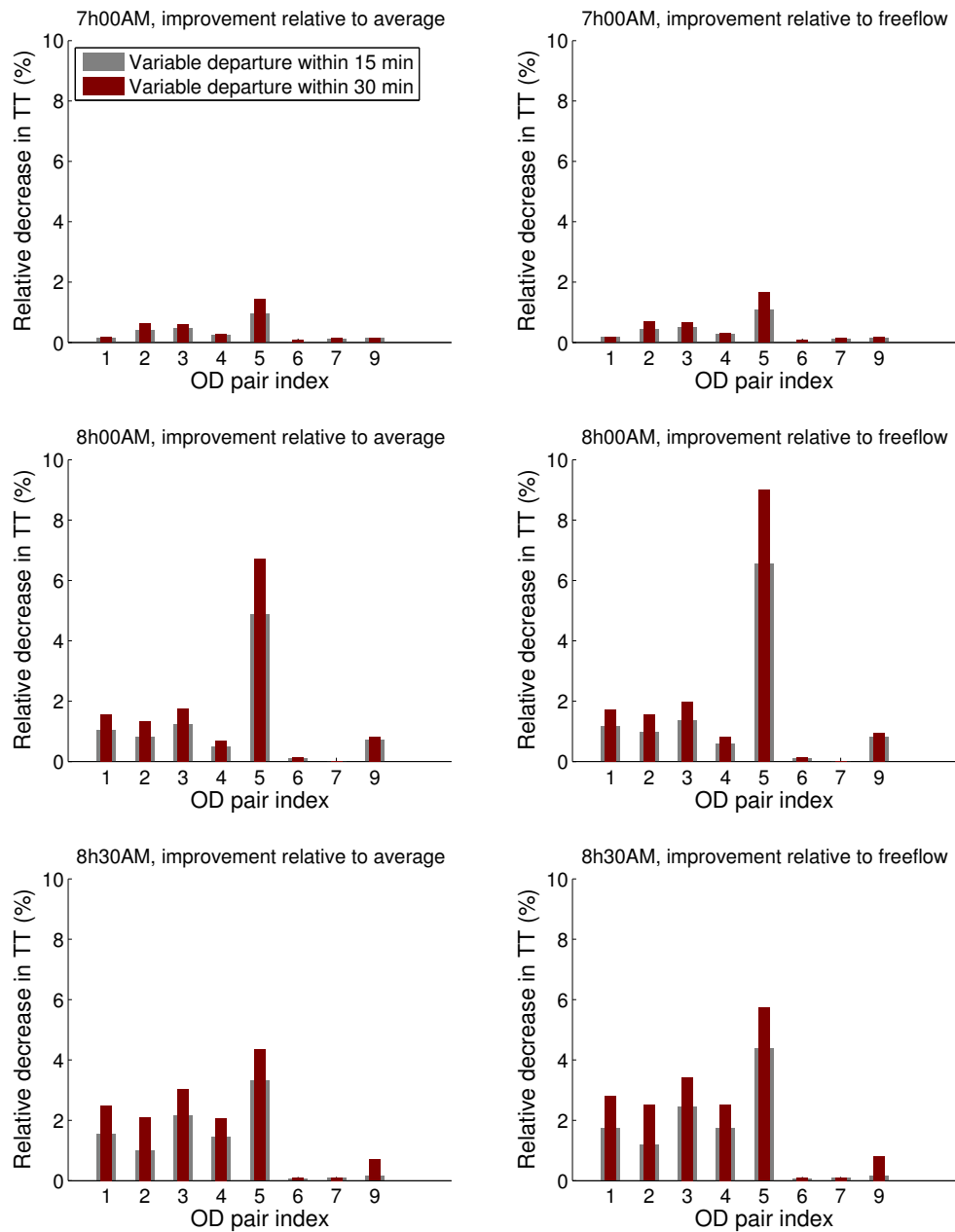


Figure 5-19: Relative decrease in delay with variable departure times, for 7h00AM, 8h00AM and 8h30AM.

- The size of the variation interval around the static departure time appears to have a significant effect, although the merits of having a larger interval stays limited to a

maximum of 1 to 2% of the average delay at the static departure time. Theoretically, the interval could be set to whatever size in order to optimize the travel time, however in practice this obviously impossible. It is therefore required to determine what interval size is worth the improvement that could be gained.

5-9 Discussion of results

This section concisely discusses the validity of the data and the results. The first subsection discusses the route set generation and travel time trajectory procedure. The second and third subsection reflect on the results of the analytic indicator and the perceived reliability analysis, respectively.

Route set generation and trajectory procedure

The validation of the coverage Ω of the generated route set generation procedure is conventionally done by comparing with actual observed routes taken by travelers. For this specific case study, no such data is present and therefore the coverage of the route set is based on expert judgement at the discretion of the modeler. In this case, the coverage of the route set is considered sufficient for the purposes of this research. It must be noted that although erroneous and duplicate routes are excluded, the deletion of irrelevant routes is not sufficient. As explained in subsection 5-5-3, the inclusion of these irrelevant routes is for the representation of the case study undesired, although for the purposes of testing the analytic indicator and determining the perceived reliability of travelers it is not critical. However, when case specific conclusion are drawn based on the results, this aspect of the route set generation procedure should be considered.

The inclusion of a variable route set per observation leads to high computation times. For the investigation of a limited amount of *OD*-pairs this is acceptable, yet when a larger network is implemented the benefits of the variable route sets are not worth the extra computation time. For such a larger network, a static route set generation procedure is better.

For the assignment of actual travel time to the generated, archived historical data is used. The implementation of historical data provided large quality and coverage of the case study area, with the exception of some of the urban roads in the center of the city of Amsterdam. In case actual travel time data was missing from the dataset, freeflow travel time was assumed for the road segment in order to prevent errors. This leads to inherent underestimation of the travel time on the lower scale of the network, affecting the results of both the analytic indicator and the perceived reliability.

Analytic indicator

The analytic indicator provides insight in the (degree of) degradation of connections as the peak hour progresses. It is harder to determine what the absolute value the indicator represents. Outside the peak hour the absolute values are stable per connection and here the difference between the connection quality can be observed when dispersion is minimal. Though

the differences in absolute value are easily determined, the exact meaning of this value is hard to determine as it consists of two variables: the number of alternatives and the dispersion. Theoretically, a connection with a large route set and large dispersion can be assigned the same value as a connection with few routes and less dispersion. Figure 5-9 and corresponding explanation shows how the absolute value is built from both variables. From this, we can determine that in order to use the relative difference of the indicated quality between two connections, it is necessary to determine the relation between the number of alternatives and dispersion in order to provide a complete assessment.

It appears that urban connections are less influenced by dispersion and remain stable over the course of the peak hour than highway connections. This may have two causes. The first cause is that as congestion originates on the higher level network, the outflow of the higher levels scale to the lower is scale remains bounded by the capacity. It may be that therefore the effect of the peak hour is less visible on the urban connections. The second cause could be the lack of data on the lower level network mentioned also for the trajectory procedure, causing travel times to remain stable as freeflow time is assumed on large parts of the connection. Note that the second cause is likely, although fluctuations in travel times are observed in the distributions indicating that actual travel times have been assigned to at least a part of the connection. In order to determine what the main cause is, further research is required.

In retrospect to the route set generation and the inclusion of irrelevant routes, the analytic indicator in its current form assigns an equal value to all routes and thus also to those irrelevant routes. For the explanatory and investigative purpose of this research this is not critical. A possible improvement on the indicator could be the inclusion of route overlap and domination in order to provide scaling among routes in the aggregation procedure.

Perceived reliability

Travel time reliability of base route, choice model and fastest path

The distributions used for the determination of perceived reliability of different traveler types are created under the assumption that the conditions during peak hour and non-peak hour intervals are homogeneous. Under this assumption, all observations are assumed to be made in similar conditions within the interval and therefore no distinction is made. This assumption is debatable for the peak hour interval, especially when regarding the results from the analytic indicator which clearly show the quality of (most of) the connections reduce as the peak hour progresses. On the other hand, the combination of all observations and application of reliability indicator hereon leads to an indication of the reliability of the travel time as the peak hour progresses. Therefore, the choice to combine all observations and the large sample size created as a results is considered justified.

A clear distinction can be made with regard to urban and highway connections. Overall, it appears as if urban connections have a higher reliability. Furthermore, the base route is in the majority of observations the fastest. Note that, in a way similar to the analytic indicator, the cause of this higher reliability may well be lack of data, which would require further investigation.

In order to improve the route choice model, the availability of floating car data is necessary. The route choice model as implemented is based on literature values and at the modelers discretion. It does show an general impression of a 'normal' traveler as a result, but is not representative of a traveler in this specific case study. As a result, conclusions based on (a comparison with) the route choice model distribution should be made with reservations.

In this research, the base route is the fastest freeflow route. This is done under the assumption that under normal conditions this is most selected route taken and the optimal route. This is the case for the majority of considered connections, however for some connections the fastest freeflow route is never the fastest, even under assumed freeflow conditions. This indicates either a constant delay on these routes or a flaw in the model where erroneous freeflow times are assigned to the routes. An other cause could be wrong assignment of actual route travel times, but after consideration of data and the results this is considered unlikely. The choice which route of a connection is the base route can be changed in correspondence with the purpose of the research.

Variable departure times

The possibility of departing within a certain time interval instead of having a static departure time provides the traveler in due time with higher travel time reliability and less average delay, improving with increasing size of the interval. Note that it is assumed that the traveler is fully informed of the fastest route at the static departure time and also fully aware what is the fastest route at the optimal time within a certain interval. This assumption is a simplification of the real situation and in order to provide better insight more detailed research into the actual degree of information a traveler possesses is required. Furthermore, the sizes of the investigated intervals are chosen at the writer discretion. It is necessary to determine what a viable interval is, considering the balance between the advantages of less delay and the disadvantages of departing later.

Chapter 6

Conclusions

The objective of the research reported in this thesis has been to give insight in the variability of route sets and travel times in a large network and how they differ depending on the *OD*-pair observed and over time. Therefrom the goal was to determine a method to determine the travel time reliability of an entire connection between an *OD*-pair through the aggregation of routes travel times. An analytic indicator from network perspective, the connectivity indicator, was developed to aggregate travel times on route level for multiple observations in time using an adapted form of the Logsum method in order to determine the reliability and quality of a connection. This indicator objectively quantifies the quality of a connection based on the number of alternatives in the route and the dispersion (reliability) of travel time. Furthermore, the perceived connection reliability was analyzed from different reference user perspectives (uninformed and normal) and several reliability indicators were explored in order to provide quantification of the perceived connection travel time reliability. This allowed for the analysis of the improvement of reliability that can be gained by implementing measures such as fastest route advice (thus being fully informed) and variable departure times for travelers in a case study. In this chapter, conclusions are drawn with regard to the theoretical basis and the practical application by answering the associated research questions.

6-1 Theoretical basis

Which aggregation methodology is appropriate to aggregate routes in a route set and to determine the quality of the connection?

For the aggregation of travel time by aggregating the travel times measures for a route set, two aggregation methods were identified: the weighted mean and the Logsum method. Based

on a set of criteria, it was determined that the weighted mean method proved inadequate. The Logsum method met most criteria and is theoretically justified, but it had side-effects which needed compensation. Therefore, an adapted version of the Logsum method was created, which remained theoretically justified and stable. This adapted version, referred to as the connectivity indicator, is dependent on the number of alternatives in a route and on the dispersion of the travel time, both elements were concluded to influence the quality of a connection. Interpretation of the outcome proved to be hard, as the indicated quality value is based on two variables (number of alternatives and the travel time dispersion). This leads to the possibility of two connections having the same indicated quality, although caused by a different ratio between the variables. This fact is logical and desirable, as the one variable can compensate for the other. The ratio between the variables provides further information about the makeup of the outcome. From this, it can be concluded that interpretation of the connectivity value is best done in interaction with the ratio of the variables in order to determine the actual reason for the indicated value. This is particularly necessary if certain improvement measures are proposed for one variable or the other. This last conclusion is corroborated by the results, which clearly indicate several connections with similar connectivity values, but with different ratio between the number of alternatives and the travel time dispersion.

What defines the perceived reliability of the user and how is this influenced by route choice?

The quality and reliability of a connection from a user perspective is determined largely dependent on the choices of the traveler and the travel time distribution corresponding with those choices. It is concluded that perceived reliability can be defined by the reliability derived from distribution of travel times of the routes taken by the user. As such, it can also be concluded that as the route choice determines the set of routes taken, the perceived reliability is dependent on the travel times of the selected routes.

6-2 Practical application

How does the connection quality depend on the time of day and on the type of connection?

The connectivity indicator showed that as peak hour progresses the quality of the connections degraded considerably. Outside of the peak hour the quality of connections remained stable, as is expected when there are no recurrent changes in dispersion. Although stable, a distinction in quality between connections could be observed. From this, it can be concluded that a distinction that the connection quality depends significantly on the time of day and that an assessment of the quality outside of the peak hour provided insight in the base quality of the connection when travel time dispersion is low.

Furthermore, a considerable difference in quality fluctuations between highway and urban connections was found. From this, it can be concluded that urban connections are less vulnerable

to peak hour quality fluctuations. However, this can be caused by the fact that as congestion originates on the higher level network, the outflow of the higher levels scale to the lower is scale remains bounded by the outflow capacity of those congested roads, thereby having less congestion on the urban road network. Another cause could be the lack of data on these roads causing the assignment of freeflow travel time on roads where no data is present. It is likely to be a combination of both causes. With regard to the base quality outside of the peak hour, it was concluded that no definite distinction could be made.

What is the relationship between the type of user and the perceived connection reliability?

The perceived travel time reliability was investigated with two reference trip travel time distributions, the fastest freeflow route or base distribution and a route choice model distribution. The fastest freeflow route was concluded to be the best single route representation of a connection, while at the same time being the most logical route choice for a uninformed traveler. The route choice model was estimated based on literature values and boundary conditions set at the modelers discretion. The resulting distributions for the route choice were concluded to be enough for a representation of a normal traveler in the case study area, although conclusions with regard to the distribution must be made with reservations. The determination of perceived travel time reliability shows that the degree of information can significantly improve the average travel time and also the travel time reliability. A clear distinction can be made between urban and highway connections. Urban connection have a higher travel time reliability. Note that, in a way similar to the analytic indicator, the cause of this higher reliability may well be lack of data, which would require further investigation. Furthermore, the base route is in the majority of observations the fastest. The implementation of a fastest path algorithm to simulate a traveler fully informed of the fastest route, improvements in reliability can be observed for almost all connections, although this effect is only really significant for the highway connections. The base route of urban connections is almost always the fastest route over all observations. From this, it can also be concluded that the fastest freeflow route is in case of no information usually a good option, although this effect can be caused by lack of data. A 'normal' traveler experiences the worst travel time reliability, although this is inherent to fact that the choice procedure for this distribution is not solely based on travel time, while the other are. These results show that informing the traveler of the situation on the network may significantly improve the travel time reliability he perceives.

When considering the possibility of having a variable departure time, it is concluded that this can have a significant advantage over a static departure time. This effect is most notable for static departure times later in the considered peak hour interval and depends on the size of the considered interval around the static departure time. For reliability, the improvements could go up to about 50%, while the delay suffered decreased to a maximum of 9%, depending on the interval size.

6-3 Model setup

The method to determine the actual travel times was the trajectory method applied on archived data, which proved to provide decent and complete results. The route set of a connection was generated with a Monte Carlo simulation using Labeling, K -shortest and a stochastic influence on link level. Per observation, the route set was reset, which led to unnecessary large computation times. The coverage of the route sets generated was determined sufficient, but could not be validated due to the lack of comparable actual observed routes.

In order to assess the travel time reliability of any travel time distribution, a selection of performance indicators has been made. For this selection a set of criteria was developed. The indicators should be simple and concise, taking skewness of the distribution into account, based on the median instead of the mean, without arbitrary parameters, well known, expressive and easily communicated and preferably convertible in a monetary expression. No single indicator met all criteria and therefore a selection of multiple indicators is chosen. It is concluded that these indicators proved to be performing well, although the Buffer time Index showed unstable behavior (large relative shifts within and between connections) and results contradictory to the other performance indicators.

Recommendations

This chapter depicts recommendations for improvement of the current framework as presented in this thesis and possible directions for further research in the future.

7-1 Recommendations for current framework

The framework developed and the application in the case study provided insight in the practical application of route aggregation from a network and user perspective, but the implications of possible improvement measures were investigated only for a limited selection of measures (information and variable departure times) from a user perspective. For the application of the connectivity indicator, we state the following:

1. The value of the connectivity indicator provides a good relative insight in connection quality, but the value itself is less expressive. It is recommended to determine a reference for what is a 'bad' connectivity value and what is 'good'. As these definitions are not very quantitative, this reference is recommended to be determined based on empirical research and expert judgment.
2. The inclusion of the ratio between the number of alternatives and the dispersion is recommended to be included in the application of the indicator, thereby indicating the make-up of the value and in what area an improvement measure should be implemented.
3. Effects of changes in the layout of the connection (e.g. the addition of an extra route) was not included and is therefore recommended in order to test the implications of such an addition for the connectivity of a connection.

4. The indicator is based on the fastest freeflow route as a reference. This reference can be changed in accordance with the research purpose.
5. The indicator now values every route in the route in the same degree, although it can be determined that certain routes are more important than other. Some routes can be even considered irrelevant as they are more or less the same as an other route. It is therefore recommended to investigate the possibility of the inclusion of overlap and/or dominance in the connectivity indicator.

The user perspective was based on the perceived reliability of travel time distributions of simplified measures in comparison to certain reference distributions. The results showed that such measures can improve the perceived reliability of the connection, but the simplification of the measures may have lead to overestimation of the benefits. It is recommended to provide a more realistic structure for the measures, listed below.

1. Estimation of the route choice model based on floating car data collected in the case study area, thereby providing a more realistic representation of the average ‘normal’ traveler.
2. The fastest path algorithm assumes full compliance of the traveler. In reality, this is not the case and it is recommended to investigate the compliance of a traveler.
3. The fastest path advice is based on user optimum (fastest travel time for the user), while this does not (necessarily) lead to a system optimum for the considered connection which ultimately considered in the network perspective. A careful consideration between network perspective and user perspective is required. This may lead to an altered algorithm, leading the traveler according to the system optimum, but this may lead to higher perceived travel times and lower reliability, making the user optimum an overestimation of the benefits of being fully informed.
4. For variable departure times, it is recommended to investigate the relation between the possible benefits of having a lower travel time and higher reliability and the fact that a later departure time is selected. If the arrival time is fixed, departing later is impossible and the only way to improve travel time and travel time reliability is to depart earlier instead of later. However, departing earlier is already most of the times possible. In case the arrival time is more flexible, the measure becomes interesting. The degree of flexibility determines the possible maximum interval size around the departure time that needs investigating. Research into how and when this can applied in practice is recommended for further research.

To improve technical aspects of the framework, we recommend the following with respect to the implemented data and route set generation:

1. Better insight in, and on a long term improvement of, the data coverage on the lower levels of the network. The assumption of freeflow times on roads with data gaps leads inherently to underestimation. On a short term we recommend a more elaborate estimation of actual travel times based extrapolation and on surrounding roads. This may lead to more realistic results instead of the assumption of freeflow speeds.
2. The effect of intersections in the network leads to variable delays that are not explicitly taken into account. Some links may include intersections, while it is possible that intersections are located at nodes, thereby having no measurements of the delay suffered by these intersections. It is recommended that on the long term measurements for these intersections are explicitly implemented in the determination of route travel times.
3. The route set generation is now variable over time, leading to high computation times. It is uncertain what benefits are to be gained by a variable route set as the coverage cannot be checked. We recommend the route set per *OD*-pair to be generated once a priori, thereby reducing computation time and improving comparability, at least while the benefits of a variable set cannot be demonstrated.

7-2 Directions for further research

Current estimation of the quality of a connection is based on the travel time and travel time reliability of a single route. Both the connectivity indicator and the implementation of a certain representativeness perceived travel time distribution can be used to indicate a different travel time and travel time reliability for the connection based on the route set of the connection instead of on just a single route. Further research is required what is in the end the best method to represent the quality of the aggregate of routes for a connection.

The methodology in this thesis is based on the morning peak and a time interval during midday. It is recommended to extend this research to other time intervals of the day, of which is most notable the evening peak hour.

The connectivity indicator is based only on travel time, which suggests that the quality of a connection is purely based on the aspect travel time. It is therefore interesting to investigate the possibility of the inclusion of utility theory in order to quantify quality of a connection. We recommend that further research into the aggregate quality of a route set includes other aspects besides travel time. For the determination of travel time reliability this is obviously not necessary.

Currently, there is the development of accessibility indexes. These indexes indicate the accessibility of a location based on travel time, perpendicular distance and the number of movements

to that location. It may be interesting for further research to assess the possibility of adding the aspect of travel reliability to such an index.

References

- Avineri, E. and Prashker, J. (2005). Sensitivity to travel time variability: Travelers' learning perspective. *Transportation Research Part C*, pages 157–183.
- Bates, J., Polak, J., Jones, P., and Cook, A. (2001). The valuation of reliability of personal travel. *Transportation Research Part E*, pages 191–229.
- Bekhor, S., Ben-Akiva, M., and Ramming, M. (2006). Evaluation of choice set generation algorithms for route choice models. *Annals of Operations Research*, 144, pages 235–247.
- Bell, M. (1999). Measuring network reliability: A game theoretic approach. *Journal of Advanced Transportation*, 33:135–146.
- Bell, M., Cassir, C., Iida, Y., and Lam, W. (1999). A sensitivity-based approach to network reliability assessment. *Proceedings: 14th International Symposium on Transportation and Traffic Theory*, pages 283–300.
- Ben-Akiva, M., Bergman, M., and Daly, A. (1984). Modelling inter urban route choice behaviour. *Proceedings: 9th International Symposium on Transportation and Traffic Theory*, pages 299–330.
- Ben-Akiva, M. and Lerman, S. L. (1985). *Discrete Choice Analysis: Theory and Application to Travel Demand*. MIT Press series in transportation studies; 9.
- Bierlaire, M. (2008). *Lecture notes: Route choice models: Introduction and recent developments*. Prepared for Transport and Mobility Laboratory, École Polytechnique Fédérale de Lausanne.
- Bierlaire, M., Frejinger, E., and Stojanovic, J. (2006). *A Latent Route Choice Model in Switzerland*.

- Billington, R. and Allan, R. (1992). *Reliability evaluation of engineering systems: Concepts & techniques*. Plenum Press Publish, New York, USA.
- Bleichrodt, H., Abellan-Perpiñan, J., Pinto-Prades, J., and Mendez-Martinez, I. (2007). Resolving inconsistencies in utility measurement under risk: tests of generalizations of expected utility. *Management Science*, 53(3):469–482.
- Bogers, E., Viti, F., and Hoogendoorn, S. (2005). Joint modeling of atis, habit and learning impacts on route choice by laboratory simulator experiments. *Transportation Research Record 1926*, pages 189–197.
- Brownstone, D. and Small, K. (2005). Valuing time and reliability: assessing the evidence from road pricing demonstrations. *Transportation Research Part A*, pages 279–293.
- Chen, A., Tatneni, M., Lee, D., and Yang, H. (2000). Effect of route choice models on estimating network capacity reliability. *Transportation Research Record 1733*, pages 63–70.
- Chen, A., Yang, H., Lo, H., and Tang, W. (2002). Capacity reliability of a road network— an assessment methodology and numerical results. *Transportation Research Part B*, pages 225–252.
- Clark, S. and Watling, D. (2005). Modelling network travel time reliability under stochastic demand. *Transportation Research Part B*, pages 119–140.
- Coifman, B. (2002). Estimating travel times and vehicle trajectories on freeways using dual loop detectors. *Transportation Research Part A*, pages 351–364.
- Connekt (2014). Praktijkproef amsterdam (ppa). <http://www.connekt.nl/nl-NL/actueel/444/praktijkproef-amsterdam-ppa.html>.
- Corthout, R. (2012). *Intersection modeling and marginal simulation in macroscopic dynamic network loading*. Katholieke universiteit Leuven.
- Corthout, R., Tampère, C., Viti, F., and Immers, L. (2014). Improving the efficiency of repeated dynamic network loading through marginal simulation. *Transportation Research C*, pages 90–190.
- De Jong, G., Daly, A., Pieters, M., and Van der Hoorn, A. (2005). *The logsum as an evaluation measure: review of the literature and new results*. The 45th Congress of the European Regional Science Association, August, 23-27.
- De Jong, G., Kouwenhoven, M., Kroes, E., Rietveld, P., and Warffemius, P. (2009). Preliminary monetary values for the reliability of travel times in freight transport. *European Journal of Transport and Infrastructure Research*, 9(2):83–99.

- De Palma, A. and Picard, N. (2005). Route choice decision under travel time uncertainty. *Transportation Research Part A*, pages 295–324.
- Dijkstra, E. (1959). A note on two problems in connexion with graphs. *Numerische Mathematik*, pages 269–271.
- Du, Z. and Nicholson, A. (1996). Degradable transportation systems: Sensitivity and reliability analysis. *Transportation Research Part B*, pages 225–231.
- Elamir, E. (2012). *On uses of mean absolute deviation: decomposition, skewness and correlation coefficients*.
- Eliasson, J. (2004). *Car drivers' valuations of travel time variability, unexpected delays and queue driving*. European Transport Conference.
- Fiorenzo-Catalano, M. (2007). *Choice Set Generation in Multi-Modal Transportation Networks*. Delft University of Technology. Dissertation.
- Fiorenzo-Catalano, M., van Nes, R., and Bovy, P. (2004). Choice set generation for multi-modal travel analysis. *European Journal of Transport and Infrastructure Research*, pages 195–209.
- Fosgerau, M., Hjorth, K., Brems, C., and Fukuda, D. (2008). *Travel time variability: Definition and valuation*. Department of Transport, Denmark, Bygningstorvet 116 Vest, 2800 Kgs. Lyngby.
- Frejinger, E., Bierlaire, M., and Ben-Akiva, M. (2009). Sampling of alternatives for route choice modeling. *Transportation Research Part B*, pages 984–994.
- Friedrich, M., Hofsäß, I., and Wekeck, S. (2001). Timetable-based transit assignment using branch and bound techniques. *Transportation Research Record, 1752*, pages 100–107.
- Google (2014). Google maps. <http://www.maps.google.com>.
- Hellinga, B. (2010). Defining, measuring, and modeling transportation network reliability. Final report.
- Hoogendoorn-Lanser, S. (2005). *Modelling Travel Behaviour in Multi-modal Networks*. Delft University of Technology. Dissertation.
- Iida, Y. and Wakabayashi, H. (1989). An approximation method of terminal reliability of a road network using partial minimal path and cut set. *Proceedings: 5th World Conference on Transport Research*, pages 367–380.
- Immers, L., Bleukx, A., Stada, J., Tampère, C., and Yperman, Y. (2004). Robustness and resilience of road network structures. *NECTAR Cluster Meeting on Reliability of Networks*.

- Knoop, V., Snelder, M., van Zuylen, H., and Hoogendoorn, S. (2012). Link-level vulnerability indicators for real-world networks. *Transportation Research Part A*, pages 843–854.
- Lam, T. and Small, K. (2001). The value of time and reliability: measurement from a value pricing experiment. *Transportation Research Part E*, pages 231–251.
- Land, A. and Doig, A. (1960). An automatic method of solving discrete programming problems. *Econometrica* 28 (3), pages 497–520.
- Li, H. (2009). *Reliability-based Dynamic Network Design with Stochastic Networks*. Transport Research Center Delft, TRAIL Research School, and The Dutch foundation “Next Generation Infrastructures”. Dissertation.
- Li, Z., Hensher, D., and Rose, J. (2009). Willingness to pay for travel time reliability in passenger transport: A review and some new empirical evidence. *Transportation Research Part E*, pages 384–403.
- Liu, H., Recker, W., and Chen, A. (2004). Uncovering the contribution of travel time reliability to dynamic route choice using real-time loop data. *Transportation Research Part A*, pages 435–453.
- Lomax, T., Schrank, D., Turner, S., and Margiotta, R. (2003). *Selecting travel time reliability measures*. Texas Transportation Institute, Cambridge Systematics Inc.
- Minderhoud, M. (2014). *Korte beschrijving Smart Routing PPA*. TNO, Smart Mobility.
- Navteq (2012). Navteq maps. <http://here.com/navteq-redirect/?lang=en-us>.
- NDW (2014). Nationale databank wegverkeergegevens. <http://www.ndw.nu/>.
- Ng, M., Szeto, W., and Waller, S. (2011). Distribution-free travel time reliability assessment with probability inequalities. *Transportation Research Part B*, pages 852–866.
- Palsdottir, K. (2011). Ex-post analysis on effects of policy measures on travel time reliability. Master thesis, Delft University of Technology, the Netherlands.
- Papinski, D., Scott, D., and Doherty, S. (2009). Exploring the route choice decision-making process: A comparison of planned and observed routes obtained using person-based gps. *Transportation Research Part F*, pages 347–358.
- Peer, S., Koopmans, C., and Verhoef, E. (2012). Prediction of travel time variability for cost-benefit analysis. *Transportation Research Part A*, pages 79–90.
- Prato, C. and Bekhor, S. (2006). *Applying branch and bound technique to route choice set generation*. The 85th Annual Meeting of the Transportation Research Board.

- Pu, W. (2011). Analytic relationships between travel time reliability measures. *Transportation Research Record: Journal of the Transportation Research Board*, pages 122–130.
- Rijkswaterstaat (2014a). About us. http://www.rws.nl/en/about_us/.
- Rijkswaterstaat (2014b). Arcadis/vid en ars/tno zetten innovatieve technologieën in de auto in om doorstroming op wegen rond amsterdam te verbeteren. http://www.rijkswaterstaat.nl/actueel/nieuws_en_persberichten/2014/januari2014/arcadisvid_en_arstno_zetten_innovatieve_technologien_in_de_auto_in_om_doorstroming_op_wegen_rond_amsterdam_te_verbeteren.aspx.
- Rijkswaterstaat (2014c). Praktijkproef amsterdam: kortere files door innovatief gebruik technologieën. http://www.rws.nl/zakelijk/innovatie/doorstroming_door_innovatie/lopende_projecten/projecten/praktijkproef_amsterdam/index.aspx.
- SHRP2 (2012). Overview of concepts, projects and implementation activities of the reliability focus area. Strategic Highway Research Program. Transportation Research Board, presentation for new members.
- Siu, B. and Lo, H. (2008). Doubly uncertain transportation network: Degradable capacity and stochastic demand. *European Journal of Operational Research* 191, pages 166–181.
- Snelder, M. and Tavasszy, L. (2010). *Quantifying the full reliability benefits of road network improvements*. Instituto Superior Técnico (IST), Lisbon, Portugal. Proceedings: 12th World Conference on Transport Research.
- Snelder, M., van Zuylen, H., and Immers, L. (2012). A framework for robustness analysis of road networks for short term variations in supply. *Transportation Research Part A*, pages 828–842.
- Stadsregio, A. (2014a). English information. <http://www.stadsregioamsterdam.nl/algemene-onderdelen/english-information/>.
- Stadsregio, A. (2014b). Praktijkproef amsterdam. <http://www.stadsregioamsterdam.nl/beleidsterreinen/infrastructuur/praktijkproef/>.
- Van der Gun, J. (2013). A flexible approach towards public transport modeling in travel demand models. Master thesis, Delft University of Technology, the Netherlands.
- Van Lint, J. and Van der Zijpp, N. (2003). An improved travel-time estimation algorithm using dual loop detectors. *Transportation Research Record* 1855, pages 41–48.
- Van Lint, J., Van Zuylen, H., and Tu, H. (2008). Travel time unreliability on freeways: Why measures based on variance tell only half the story. *Transportation Research Part A*, pages 258–277.

- Wakabayashi, H. and Iida, Y. (1992). Upper and lower bounds of terminal reliability of road networks: an efficient method with boolean algebra. *Journal of Natural Disaster Science*, 14:29–44.
- Warffemius, P. (2002). De maatschappelijke waarde van kortere en betrouwbaardere reistijden (dutch). Technical report, Kennisinstituut voor Mobiliteitsbeleid. Ministerie van Infrastructuur en Milieu.
- Wesseling, B. (2013). Forecasting door-to-door travel time variability caused by incidents. Master thesis, Delft University of Technology, the Netherlands.
- Xu, H., Zhou, J., and Xu, W. (2011). A decision-making rule for modeling travelers' route choice behavior based on cumulative prospect theory. *Transportation Research Part C*, pages 218–228.

Appendix A

Route choice model

The estimation of the route choice model is based on literature values. The formulation and estimation of the parameters of the components is based on Lam and Small (2001), Bekhor et al. (2006) and Bierlaire et al. (2006). As not every study held the same components, estimation of the complete function is based on expert judgment.

A set of boundary conditions is determined, followed by a concise sensitivity analysis based on a single connection from the case study.

Parameter values and utility functions

Estimated values from literature are represented in table 5-6. Note that the values a and b are a representation of the mutual relationship between parameters that cannot be derived directly from literature.

β parameter	Value
ln(PS)	1
Mean	β_a^*
SD	$3.71 \cdot \beta_a^*$
Median	β_b^*
Perc90 minus median	$1.77 \cdot \beta_b^*$
Proportion highway	-2.2
Proportion urban roads	-4.4

Table A-1: Parameter values for route choice modeling.

Considering table 5-6, the utility functions can be rewritten as represented in equations (5-2) and (5-3).

$$U_{mean-variance,p} = \beta_a^* [\mu + f_\sigma \cdot \sigma_p] + \beta_c^* [\ln(PS_p) + f_{HW} \cdot \xi_{HW} + f_{urb} \cdot (1 - \xi_{HW})] \quad (A-1)$$

$$U_{median-perc,p} = \beta_b^* [med + f_{perc90} \cdot \tau_{90\%-50\%}] + \beta_c^* [\ln(PS_p) + f_{HW} \cdot \xi_{HW} + f_{urb} \cdot (1 - \xi_{HW})] \quad (A-2)$$

where the β^* values represent parts of the utility function that are dependent of each other and the different f_i values express the ratio within these dependent parts. At first glance, it can be determined that $\beta_c^* = \beta_{PS} = 1$ and the ratio values f are the remaining β parameters from table 5-6.

As the main focus of this thesis lies on travel time and travel time reliability, it is therefore logical to make sure these are well represented in the parameters. The relation between the travel time and travel time reliability parameters is already known; these follow from literature. The value of $\phi =$ is set to -1 for the route choice model.

Boundary conditions

For now, we focus on the mean-variance utility function. Considering the situation of n routes where the road proportions are the same but the overlap is not. The road proportion parameters can be canceled out of the equation temporarily. We consider 2 routes from the selection of n , where route 1 has no overlap and route 2 has complete overlap. Although route 1 has no overlap, we assume that travel time remains dominant, thus if route 2 is faster the utility (U_2) of this route should always be higher than U_1 .

This leads to the following, as the β parameter for overlap is 1:

$$U_1 \leq U_2 \quad (A-3)$$

$$\beta(\mu + \delta_\mu) + \ln(PS_1) \leq \beta\mu + \ln(PS_2) \quad (A-4)$$

$$(A-5)$$

As the boundaries for the PS-value are $1/n$ for complete overlap en 0 for no overlap the equation becomes:

$$\beta(\mu + \delta_\mu) + \ln(1) \leq \beta\mu + \ln\left(\frac{1}{n}\right) \quad (\text{A-6})$$

$$\beta\mu + \beta\delta_\mu + 0 \leq \beta\mu + \ln\left(\frac{1}{n}\right) \quad (\text{A-7})$$

$$\beta\delta_\mu + \leq \ln\left(\frac{1}{n}\right) \quad (\text{A-8})$$

$$\beta \leq \frac{\ln\left(\frac{1}{n}\right)}{\delta_\mu} \quad (\text{A-9})$$

$$\beta \leq -\frac{\ln(n)}{\delta_\mu} \quad (\text{A-10})$$

This hypothetical boundary at the right side of the equation decreases as the number of involved routes n increases. The average route set size of the case study is 6.4 routes per set, which therefore also considered to be the value of n for the boundary condition. This leads to the boundary depicted in (A-11).

$$\beta \leq -\frac{1.9}{\delta_\mu} \quad (\text{A-11})$$

A similar example can be considered, only now we consider 2 routes, one is completely highway, the other is completely urban. There is no overlap and the reliability of both routes is the same. We assume that if though the highway route has a mean that is δ_μ higher, the highway route should be selected as the assumption is made that comfort is worth a small detour. A similar process can be performed as with the previous example, depicted below. Values for the β parameters for the proportions is derived from table A-1.

$$\beta(\mu + \delta_\mu) + \beta_{urb}(1 - \xi_{HW}) + \beta_{HW}\xi_{HW} \geq \beta\mu + \beta_{urb}(1 - \xi_{HW}) + \beta_{HW}\xi_{HW} \quad (\text{A-12})$$

$$\beta\mu + \beta\delta_\mu + 0 + \beta_{HW} \cdot 1 \geq \beta\mu + \beta_{urb} \cdot 1 + 0 \quad (\text{A-13})$$

$$\beta\delta_\mu + \beta_{HW} \geq \beta_{urb} \quad (\text{A-14})$$

$$\beta\delta_\mu - 2.2 \geq -4.4 \quad (\text{A-15})$$

$$\beta \geq \frac{-2.2}{\delta_\mu} \quad (\text{A-16})$$

With the following examples, we set the boundary conditions for the β value. For the deviation a representative value must be selected. This deviation can be chosen arbitrarily, in this thesis we set this value to 5 minutes, but this can be changed at discretion of the researcher. Note that the representative value of this route choice model is purely demonstrative, as it is not derived from a case specifically. Also note that the value of deviation selected, δ_{med} , may

be different for the median-percentile variant of the utility function, as the deviation δ_μ is assumed to be from the average. As we have no reason to select a different value for δ_{med} we set this value also to 5 minutes.

This leads to the following boundary conditions:

$$-0.44 \leq \beta_a^*, \beta_b^* \leq -0.37 \quad (\text{A-17})$$

Sensitivity analysis of Beta-parameters

This section provides a concise sensitivity analysis with regard to the β^* parameters within the boundaries set in the previous section. The analysis is based on a single case study connection, in this case #1.

The parameters β^* are tested within the boundary interval and the effect on the travel time distributions of all observations aggregated is represented in figure A-1. The parameter values are represented increasing from right to left.

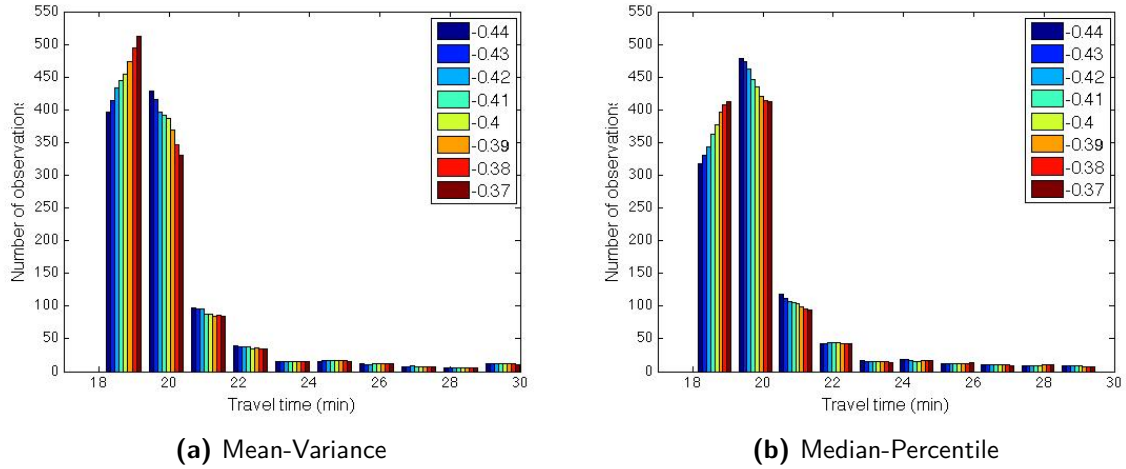


Figure A-1: Travel time distribution for several parameter value of β

These figures illustrate that a small change in parameter significantly affects the travel time distributions. In order to determine an indication of the reliability of these distributions, we apply the standard deviation. Note that the parameter change is defined by the function

$$\beta_k = -0.37 - k \cdot \text{stepsize} \quad (\text{A-18})$$

where $k = [0, 1, \dots, 7]$ and the chosen stepsize is 0.01, leading to $\beta_0 = -0.37$ and $\beta_7 = -0.44$. The mean and standard deviation of both the mean-variance and the median-percentile utility functions are expressed in figures A-2 and A-3, respectively.

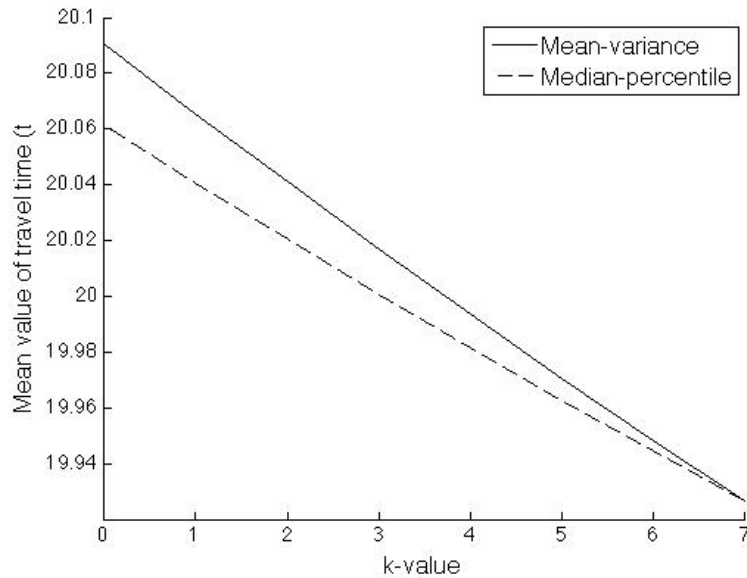


Figure A-2: Mean value of travel time per value of k

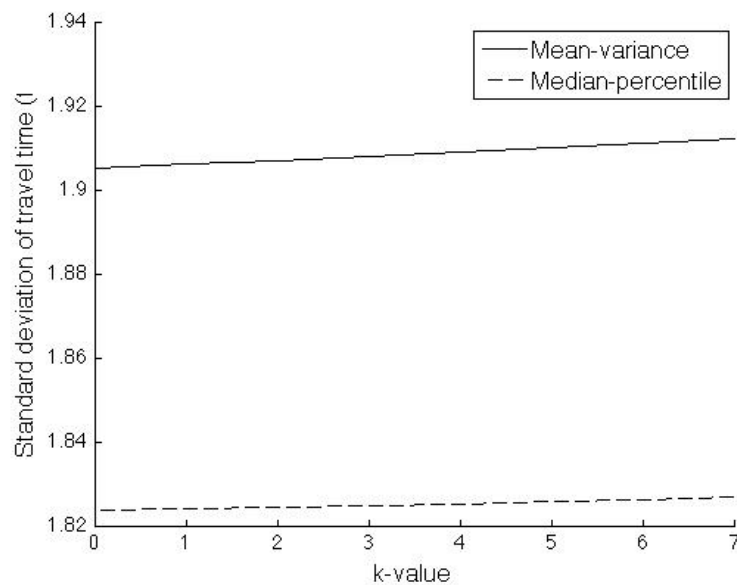


Figure A-3: Standard deviation of travel time per value of k

Although the travel distributions seem to be significantly different per change in parameter β^* , the change in mean and reliability is almost negligible. The difference between the mean-variance and median-percentile is small, but seems to be slightly in the advantage of the median-percentile function. Therefore, for the representation of the route choice, we select the median-percentile utility function, as it shows a lower mean and a more favorable standard deviation.

For the parameter β^* (both a and b , although we will only use b) we select the value of -0.37, as the reliability decreases with the increase of k . Although the average value decreases with the increase of k , the β parameters in table A-1 show that reliability is more highly valued than travel time and as both differences are small, a more reliable distribution is selected.

Appendix B

Stability of the connectivity indicator

This Appendix gives a concise and mathematical explanation of the stability of the connectivity indicator methodology. Here we focus on behavior with respect to (1) the size of the differences between observed route travel times and the freeflow time of the base route (i.e. delay) and (2) the influence of the number of alternatives included. With regard to both aspects, stable behavior is desired.

Increase in delay

Consider the connectivity indicator:

$$I_t^{conn} = \frac{1}{\phi \tau_{ff}^b} \ln \left[\sum_{p \in \mathcal{C}^{rs}} \exp(\phi \cdot (\tau_{t,p} - \tau_{ff}^b)) \right] + 1 \quad (\text{B-1})$$

We refer to this function from now on as f . For simplicity, the freeflow perspective is temporarily disregarded. When using derivatives, constant values (in this case the value 1) can be disregarded as well. This leads to the simplified formulation depicted in (B-2).

$$f(\tau) = \frac{1}{\phi} \ln \left[\sum_i^n \exp(\phi \cdot (\tau_i - \tau_{ff})) \right] \quad (\text{B-2})$$

As we investigate behavior with regard to changes in delay, the number of alternatives n is considered constant for now. Now we assume a change in the travel time of a single route with travel time τ_1 . The other $n - 1$ routes are assumed not to change. To determine the

effect of this change, the partial derivative of f with respect to τ_1 is required to determine how the function behaves after such a change.

$$f(\tau) = \frac{1}{\phi} \ln \left[\sum_i^n \exp(\phi \cdot (\tau_i - \tau_{ff})) \right] \quad (\text{B-3})$$

$$= \frac{1}{\phi} \ln [g(\tau)] \quad (\text{B-4})$$

Thus leading to

$$g(\tau) = \sum_i^n \exp(\phi \cdot (\tau_i - \tau_{ff})) \quad (\text{B-5})$$

$$\frac{\partial g}{\partial \tau_1} = \phi \exp(\phi \cdot (\tau_1 - \tau_{ff})) \quad (\text{B-6})$$

From here we can determine the partial derivative of f with respect to τ_1

$$\frac{\partial f}{\partial \tau_1} = \frac{1}{\phi} \frac{1}{g(\tau)} \frac{\partial g}{\partial \tau_1} \quad (\text{B-7})$$

$$= \frac{1}{\phi} \frac{\phi \exp(\phi \cdot (\tau_1 - \tau_{ff}))}{\sum_i^n \exp(\phi \cdot (\tau_i - \tau_{ff}))} \quad (\text{B-8})$$

$$= \frac{\exp(\phi \cdot (\tau_1 - \tau_{ff}))}{\sum_i^n \exp(\phi \cdot (\tau_i - \tau_{ff}))} \quad (\text{B-9})$$

$$= \frac{\exp(\tau_1 - \tau_{ff}) \cdot \exp(\phi)}{\sum_i^n \exp(\tau_i - \tau_{ff}) \cdot \exp(\phi)} \quad (\text{B-10})$$

$$= \frac{\exp(\tau_1 - \tau_{ff})}{\sum_i^n \exp(\tau_i - \tau_{ff})} \quad (\text{B-11})$$

Equation (B-11) appears to be a basic logit formulation. Furthermore, we know that $\tau_i \geq \tau_{ff}$. From this we can determine that the partial derivative with respect to travel time belonging to a single route is bounded as is depicted in (B-12), despite the value of change.

$$0 \leq \frac{\partial f}{\partial \tau_1} \leq 1 \quad (\text{B-12})$$

The same holds for any other route. From this we can conclude that a change in a single route has a bounded influence on the behavior of the method, thereby contributing to stable results.

Increasing number of alternatives

When determining the connectivity of an *OD*-pair, having multiple alternatives has a positive effect on the connectivity value. However, at some point the effect of having one extra alternative is expected to mitigate. It is highly unlikely that having 30 instead 29 optional routes really holds an significant improvement. In this case, the method should incorporate this effect when the number of alternatives increases.

As the number of alternative route n is a discrete variable in this section, we determine the effect of having more routes by analyzing the difference in aggregate value discretely. As is done in section B, we again refer to the connectivity with function f , although now we assume the n to be variable and τ to be a determined set of travel times. This leads to the comparison $f(n+1) - f(n)$. Again, the constant values cancel each other as the difference is investigated. Therefore, the constant of value 1 can be removed in advance.

$$f(n+1) - f(n) = \frac{1}{\phi} \ln \left[\left(\sum_i^{n+1} \exp(\phi \cdot (\tau_i - \tau_{ff})) \right) - \frac{1}{\phi} \ln \left(\sum_i^n \exp(\phi \cdot (\tau_i - \tau_{ff})) \right) \right] \quad (\text{B-13})$$

$$= \frac{1}{\phi} \ln \left[\frac{\sum_i^{n+1} \exp(\phi \cdot (\tau_i - \tau_{ff}))}{\sum_i^n \exp(\phi \cdot (\tau_i - \tau_{ff}))} \right] \quad (\text{B-14})$$

$$= \frac{1}{\phi} \ln \left[\frac{\exp(\phi \cdot (\tau_{n+1} - \tau_{ff})) + \sum_i^n \exp(\phi \cdot (\tau_i - \tau_{ff}))}{\sum_i^n \exp(\phi \cdot (\tau_i - \tau_{ff}))} \right] \quad (\text{B-15})$$

$$= \frac{1}{\phi} \ln \left[\underbrace{1 + \frac{\exp(\phi \cdot (\tau_{n+1} - \tau_{ff}))}{\sum_i^n \exp(\phi \cdot (\tau_i - \tau_{ff}))}}_{h(n)} \right] \quad (\text{B-16})$$

We find for $h(n)$:

$$h(n) = \ln \left(1 + \frac{\exp(\phi \cdot (\tau_{n+1} - \tau_{ff}))}{\sum_i^n \exp(\phi \cdot (\tau_i - \tau_{ff}))} \right) \quad (\text{B-17})$$

As we can state that since the freeflow travel time of the base route is by definition also the minimum possible travel time

$$t_i \geq t_{ff} \quad (\text{B-18})$$

This, and a conversion similar as in (B-10) where $\exp(\phi)$ is canceled out, leads to

$$\min(\exp(\tau_i - \tau_{ff})) = 1 \quad (\text{B-19})$$

$$\min\left(\sum_i^n \exp(\tau_i - \tau_{ff})\right) = n \cdot \min(\exp(\tau_i - \tau_{ff})) = n \quad (\text{B-20})$$

$$\sum_i^n \exp(\tau_i - \tau_{ff}) \geq n \quad (\text{B-21})$$

From this we can determine the limit of the fraction part of $h(n)$ when $n \rightarrow \infty$. Considering this fraction and the result from B-21 leads to

$$\frac{\exp(\tau_{n+1} - \tau_{ff})}{\sum_i^n \exp(\tau_i - \tau_{ff})} \leq \frac{\exp(\tau_{n+1} - \tau_{ff})}{n} \quad (\text{B-22})$$

For the second part of (B-22), the limit can be determined assuming the numerator to be a finite value (travel time is always finite).

$$\lim_{n \rightarrow \infty} \frac{\exp(\tau_{n+1} - \tau_{ff})}{n} = 0 \quad (\text{B-23})$$

This and the inequality depicted in (B-22) evidently leads to

$$\lim_{n \rightarrow \infty} \frac{\exp(\tau_{n+1} - \tau_{ff})}{\sum_i^n \exp(\tau_i - \tau_{ff})} = 0 \quad (\text{B-24})$$

As the limit of the fraction is 0, the limit of $h(n)$ becomes

$$\lim_{n \rightarrow \infty} h(n) = 0 \quad (\text{B-25})$$

and thus subsequently we can determine the limit of the entire method when $n \rightarrow \infty$ using the the limit of $h(n)$ as depicted in (B-26).

$$\lim_{n \rightarrow \infty} f(n) = \frac{1}{\phi} \left[\lim_{n \rightarrow \infty} h(n) \right] = 0 \quad (\text{B-26})$$

From this we can conclude that when the number of alternatives increases, the effect on the connectivity indicator is mitigated. This is perfectly in line with the desired behavior of the

method. Furthermore, we can determine that when n becomes larger, the method will not become unstable.

The degree of mitigation over the number of alternatives is dependent on model parameter ϕ . A sensitivity analysis of the influence of this parameter is performed in Appendix C.

Appendix C

Sensitivity analysis of arbitrary model parameters

The value of Phi

The model parameter ϕ determines how the connectivity indicator is influenced by the number of alternatives and the travel time dispersion. This value of this model parameter is determined at discretion of the modeler. In this thesis, the value of -0.3 is selected. In this section, the sensitivity of the model outcome to changes in this parameter value is investigated. This is done for the values -0.27 (-10%) and -0.33 (+10%) for both the peak hour and non-peak hour scenario. The effect of changes in the value of ϕ is determined by comparing the change in the average connectivity indicator value and the corresponding ratio between the number of alternatives and the travel time dispersion. The relative results are presented in tables C-1 through C-4.

<i>OD-pair index</i>	Change in average connectivity value (%)	Change in ratio (%)
1	-5	-5
2	-5	-5
3	-4	-6
4	-4	-8
5	-8	-5
6	-3	-2
7	-3	-5
9	-3	-13

Table C-1: Relative changes of model outcome between 7h00PM and 10h00PM for $\phi = -0.27$.

<i>OD-pair index</i>	Change in average connectivity value (%)	Change in ratio (%)
1	4	4
2	6	5
3	5	5
4	5	7
5	8	4
6	3	2
7	3	5
9	3	11

Table C-2: Relative changes of model outcome between 7h00PM and 10h00PM for $\phi = -0.33$.

<i>OD-pair index</i>	Change in average connectivity value (%)	Change in ratio (%)
1	-2	-5
2	-2	-6
3	-3	-7
4	-4	-9
5	-4	-6
6	-3	-2
7	-3	-5
9	-3	-11

Table C-3: Relative changes of model outcome between 12h00PM and 15h00PM for $\phi = -0.27$.

<i>OD-pair index</i>	Change in average connectivity value (%)	Change in ratio (%)
1	3	4
2	1	6
3	4	5
4	4	7
5	4	5
6	3	4
7	3	4
9	2	11

Table C-4: Relative changes of model outcome between 12h00PM and 15h00PM for $\phi = -0.33$.

The results show that a decrease in ϕ consistently leads to lower connectivity values, while an increase leads to higher values. These changes (increase and decrease) are of the same degree, from which it can be concluded that the sensitivity of the model outcome to a decrease in ϕ is similar to an increase with regard to the connectivity value outcome. The ratio represents the relative influence of the number of alternatives and the travel time dispersion. It can be determined that a decrease in ϕ leads to a higher influence of the number of alternatives, while conversely the travel time dispersion becomes more prominent with an increase in value for ϕ .

The relative size of the changes is significant, especially in the peak hour, with a maximum change of $\pm 8\%$. It can be determined that the outcome remains stable enough when small changes to the value of ϕ are assumed as the relative changes remain lower than the relative

change in model parameter. Then again, the relative changes are large enough to conclude that the model parameter ϕ is important and that further investigation in the determination of its value is required.

Route generation parameters

In this section the sensitivity of the model with regard to certain parameter settings of the route set generator is determined. The effect of small parameter changes is determined by comparing the average route size. The effect of the average route set size is in its turn determined by comparing the change in the average connectivity indicator value and the corresponding ratio between the number of alternatives and the travel time dispersion.

Speed threshold parameter

The speed threshold parameter ζ_{thres} is a discrete parameter with a select number of possible settings. In table C-5 the possible setting values for the implemented route set generator are presented.

Value of ζ_{thres} (km/h)	Number of links with speed above threshold
0	45926
30	45926
50	27757
70	20304
90	5403

Table C-5: Links included in stochastic simulation depending on the value of ζ_{thres}

The model outcome sensitivity to this parameters setting is explored by setting the threshold to 30 and 70 km/h and comparing it to the reference outcome for $\zeta_{thres} = 50$ km/h. The relative results are presented in tables C-6 through C-9, thereby also comparing the differences between the peak and non-peak scenario.

OD-pair index	Change in average route set size (%)	Change in average connectivity (%)	Change in average value	Change in ratio (%)
1	0	0	0	0
2	0	0	0	0
3	0	0	0	0
4	0	0	0	0
5	0	0	0	0
6	0	0	0	0
7	0	0	0	0
9	0	0	0	0

Table C-6: Relative changes of model outcome between 7h00PM and 10h00PM for $\zeta_{thres} = 30$ km/h.

The results show that the model outcome is not sensitive to adjustments to this parameter. From this, it can be concluded that the route set generation is largely dependent on the link variance on roads above the threshold of 70 km/h. It is therefore interesting to set this

<i>OD</i> -pair index	Change in average route set size (%)	Change in average connectivity (%)	Change in average value	Change in ratio (%)
1	0	0		0
2	0	0		0
3	0	0		0
4	0	0		0
5	-1	0		1
6	0	0		0
7	0	0		0
9	0	0		0

Table C-7: Relative changes of model outcome between 7h00PM and 10h00PM for $\zeta_{thres} = 70$ km/h.

<i>OD</i> -pair index	Change in average route set size (%)	Change in average connectivity (%)	Change in average value	Change in ratio (%)
1	0	0		0
2	0	0		0
3	0	0		0
4	0	0		0
5	0	0		0
6	0	0		0
7	0	0		0
9	1	0		0

Table C-8: Relative changes of model outcome between 12h00PM and 15h00PM for $\zeta_{thres} = 30$ km/h.

<i>OD</i> -pair index	Change in average route set size (%)	Change in average connectivity (%)	Change in average value	Change in ratio (%)
1	0	0		0
2	0	0		0
3	0	0		0
4	0	0		0
5	0	0		0
6	0	0		0
7	0	0		0
9	1	0		0

Table C-9: Relative changes of model outcome between 12h00PM and 15h00PM for $\zeta_{thres} = 70$ km/h.

threshold high so that less links are stochastically influenced as this has little effect. This may improve the computation time of the model.

Link travel time variance parameter

The link travel time variance is the parameter that determines the degree of variance applied in the Monte Carlo simulation. This parameter is originally set to 35% of the link travel time ($\zeta_{var} = 0.35$). The model outcome sensitivity to the link variance is determined by adjusting the parameter to 0.315 (-10%) and 0.385 (+10%). The relative results are presented in tables C-10 through C-13, thereby also comparing the differences between the peak and non-peak scenario.

<i>OD-pair index</i>	Change in average route set size (%)	Change in connectivity (%)	average value	Change in ratio (%)
1	-4	1		1
2	-3	0		0
3	-4	1		1
4	0	-1		-1
5	-4	1		2
6	0	0		0
7	0	0		0
9	-2	0		-1

Table C-10: Relative changes of model outcome between 7h00PM and 10h00PM for $\zeta_{var} = 0.315$.

<i>OD-pair index</i>	Change in average route set size (%)	Change in connectivity (%)	average value	Change in ratio (%)
1	2	0		-1
2	4	0		0
3	2	-1		-1
4	0	1		1
5	4	-1		-2
6	0	0		0
7	0	0		0
9	2	0		1

Table C-11: Relative changes of model outcome between 7h00PM and 10h00PM for $\zeta_{var} = 0.385$.

The results show that the model outcome is significantly sensitive to adjustments to the link travel time variance. It can be determined that the influence is most notable on the change in average route set size. From this, it can also be concluded that the relative change in the connectivity indicator results is smaller than the change in the route set size and that the results are similar for both time scenarios. Most importantly, a $\pm 10\%$ change in the link travel time variance has a convergent effect on the change in average route set size. This has, in turn, a convergent effect on the results of the connectivity indicator. This means that the model with regard to this parameter is stable and that small changes in link travel time variance do no result in large changes in model outcome.

<i>OD-pair index</i>	Change in average route set size (%)	Change in average connectivity (%)	Change in average value	Change in ratio (%)
1	-5	1		0
2	-4	0		-1
3	-3	1		1
4	0	-1		-1
5	-4	1		1
6	0	0		0
7	0	0		0
9	-2	0		-1

Table C-12: Relative changes of model outcome between 12h00PM and 15h00PM for $\zeta_{var} = 0.315$.

<i>OD-pair index</i>	Change in average route set size (%)	Change in average connectivity (%)	Change in average value	Change in ratio (%)
1	2	-1		0
2	4	0		1
3	2	-1		0
4	0	1		1
5	4	-1		-1
6	0	0		0
7	0	0		0
9	2	0		1

Table C-13: Relative changes of model outcome between 12h00PM and 15h00PM for $\zeta_{var} = 0.385$.

Number of simulations

The route set generator uses a Monte Carlo simulation, applying stochastically distributed link travel times for number of x simulations. This parameter is originally set to 50 simulations ($x = 50$). The model outcome sensitivity to the number of simulations is determined by adjusting the parameter to 45 (-10%) and 55 (+10%) simulations. The relative results are presented in tables C-14 through C-17, thereby also comparing the differences between the peak and non-peak scenario.

<i>OD-pair index</i>	Change in average route set size (%)	Change in average connectivity (%)	Change in average value	Change in ratio (%)
1	-1	0		0
2	0	0		0
3	-1	0		0
4	0	0		0
5	-1	0		1
6	0	0		0
7	0	0		0
9	0	0		0

Table C-14: Relative changes of model outcome between 7h00PM and 10h00PM for $x = 45$.

<i>OD-pair index</i>	Change in average route set size (%)	Change in average connectivity (%)	Change in average value	Change in ratio (%)
1	1	0		0
2	0	0		0
3	0	0		0
4	0	0		0
5	0	0		0
6	0	0		0
7	0	0		0
9	0	0		0

Table C-15: Relative changes of model outcome between 7h00PM and 10h00PM for $x = 55$.

<i>OD-pair index</i>	Change in average route set size (%)	Change in average connectivity (%)	Change in average value	Change in ratio (%)
1	-1	0		0
2	-1	0		0
3	-1	0		0
4	0	0		0
5	0	0		0
6	0	0		0
7	0	0		0
9	0	0		0

Table C-16: Relative changes of model outcome between 12h00PM and 15h00PM for $x = 45$.

<i>OD-pair index</i>	Change in average route set size (%)	Change in average connectivity (%)	Change in average value	Change in ratio (%)
1	-1	0		0
2	-1	0		0
3	-1	0		0
4	0	0		0
5	0	0		0
6	0	0		0
7	0	0		0
9	0	0		0

Table C-17: Relative changes of model outcome between 12h00PM and 15h00PM for $x = 55$.

The results show that the model outcome is not sensitive to the number of simulations. From this, it can be concluded that the number of simulations is sufficient in order to find the majority of possible feasible routes using link travel time variance. As a small decrease in the number of simulations leads to similar results, it might be for interesting future purposes to adjust the number of simulations to a lower number in order to save computation time.

Summary

For the model parameter ϕ , the results show that a decrease in ϕ consistently leads to lower connectivity values, while an increase leads to higher values. These changes (increase and decrease) are of the same degree, from which it can be concluded that the sensitivity of the model outcome to a decrease in ϕ is similar to an increase with regard to the connectivity value outcome. It can also be determined that a decrease in ϕ leads to a higher influence of the number of alternatives, while conversely the travel time dispersion becomes more prominent with an increase in value for ϕ . The relative size of the changes is significant, especially in the peak hour, with a maximum change of $\pm 8\%$. It can be determined that the outcome remains stable enough when small changes to the value of ϕ are assumed as the relative changes remain lower than the relative change in model parameter. Then again, the relative changes are large enough to conclude that the model parameter ϕ is important and that further investigation in the determination of its value is required.

The results show that the model outcome is not sensitive to adjustments to the speed threshold parameter. It can be concluded that the route set generation is largely dependent on the link variance on roads above the threshold of 70 km/h. It is therefore interesting to set this threshold high so that less links are stochastically influenced as this has little effect. This may improve the computation time of the model.

The results show that the model outcome is significantly sensitive to adjustments to the link travel time variance. It can be determined that the influence is most notable on the change in average route set size. From this, it can also be concluded that the relative change in the connectivity indicator results is smaller than the change in the route set size and that the results are similar for both time scenarios. Most importantly, a $\pm 10\%$ change in the link travel time variance has a convergent effect on the change in average route set size. This has, in turn, a convergent effect on the results of the connectivity indicator. This means that the model with regard to this parameter is stable and that small changes in link travel time variance do no result in large changes in model outcome.

The results show that the model outcome is not sensitive to the number of simulations. From this, it can be concluded that the number of simulations is sufficient in order to find the majority of possible feasible routes using link travel time variance. As a small decrease in the number of simulations leads to similar results, it might be for interesting future purposes to adjust the number of simulations to a lower number in order to save computation time.