BSc Thesis

Verifying The Practical Use Of The Schedule Based Method

Figure 1: VIRM Train (rhemkes, 2019)

Author: Karsten Hilbrands

Internal Supervisor: Dr. Konstantinos Gkiotsalitis

External Supervisor: Dr. ir. Ties Brands

Goudappel Coffeng - University of Twente

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PREFACE

This thesis is the final step of my bachelor in Civil Engineering. It is the result of 13 weeks conducting my bachelor research at Goudappel Coffeng. After successfully completing this part, I will receive my Bachelor's degree in Civil Engineering at the University of Twente in Enschede.

Goudappel Coffeng has provided me with the assignment and the resources to carry it out. Goudappel Coffeng is a consulting company in mobility. The company is active in almost all aspects of transportation. They have approximately 200 employees divided between their five offices across The Netherlands (Goudappel Coffeng, 2019). I liked working at Goudappel and I thank the company for their resources, which made this thesis possible.

I would like to show my gratitude to the people who have made this possible for me. At the company, Ties Brands was my supervisor, he is a consultant in public transport. Ties did this together with Dennis Roelofsen. Dennis is also a consultant within the public transport department of Goudappel Coffeng. I am very thankful for their help and the good conversations we had, which pushed me in the right directions. I would also like to thank Konstantinos Gkiotsalitis, my supervisor from the University. The useful feedback he gave, brought my thesis to a higher level.

I would like to give a special mention to Jamie Cook, who is a consultant at VLC. Jamie made changes to the algorithm in order it to make it work correctly, he also helped me in understanding the algorithm better. Further, I thank the colleagues at the 'flex plein', who helped me with a lot of issues in OmniTRANS. I also want to pay my gratitude to my family, friends and roommates, for their support. In the end, I would like to thank Roos for her endless support, before and during the bachelor assignment.

SUMMARY

To predict (passenger)loads on public transport services, models have to be used. Determination of loads, is called a route assignment. Two methods are used to perform the assignment, these are schedule based and frequency based methods. The frequency based method is a static assignment method, which makes no use of time. The schedule based method is a dynamic method, which does take time into account.

Schedule based methods provide more detailed calculations. These highly detailed calculations, require more input and are the cause of high computation times. Frequency based methods cannot make very detailed calculations. The low level of detail makes it easier to make calculations when limited data is available. Computation times of the frequency based assignment are also much smaller. In practice frequency based method are used more.

There is a lot of understanding in the improvements a schedule based approach can provide in theoretical sense. However, current literature lacks at giving a clear practical comparison between schedule and frequency based approaches. It is not known how large the improvements are and to what extend certain situations need to be modelled with schedule base methods.

This study must: give more insights in the schedule based algorithm, facilitate the use of this method and gain more knowledge about the benefits of the schedule based method compared to the disadvantages. A recommendation in the usage of both methods should also be given. The main research question is: *What are the main differences between the schedule based and frequency based methods in a practical application and what influences these differences?*

A case study is used to analyse the differences between the methods and to get more understanding in the schedule based method. The study is carried out on a model of the Dutch rail network, inside the OmniTRANS software package. First, a verification of the schedule based results is carried out. This is done by comparing the in-vehicle travel time. Next, all skim results are compared. Differences between the results of both methods become clear by this method. At last, a sensitivity analysis is done with the schedule based method. This is done to see the influence of certain parameters on the run-time and the skim results. From the sensitivity analysis, a good configuration of the schedule based method can be derived.

The results of the case study show that travel times from the schedule based assignments are higher on average. Transfer waiting times came out to be lower on average for the schedule based method, which results in total lower waiting times. It can also be seen that median travel times for OD-pairs with the same characteristics are almost equal for both methods. The sensitivity analysis makes clear that the branch and bound and access waiting time settings have large influence.

There are many differences between the schedule based and frequency based methods. Many differences can be found in the application of the methods. Other route choices, caused by the temporal aspects of the schedule based method, are the reason for larger overall travel times. Transfer time calculation seems to be done more accurately by schedule based methods. Overall, the schedule based method also gives results closer to the ‘real world’ travel times. It can be said that for some scenarios the schedule based method is a better way of assigning travellers on routes.

It is recommended to use schedule based assignments in situation were a lot of data is already available. It is not recommended to use these schedule based assignments for future planning purposes or quick scans of situations. When an in-depth analysis of a situation needs to be modelled a schedule based method is recommendable, especially in situations where transfers are required.

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1. INTRODUCTION

In this chapter the subject of this study is presented. First a motivation is given and then a literature review is done to come to a problem statement. Subsequently the research questions are formulated and a lay out of the research is given.

1.1 MOTIVATION

Since the start of the industrial revolution, public transport plays an important role in mobility. Recent developments, as congested roads and climate change, are causing an even larger load on public transport. These increased loads create the need for a better and higher quality public transport. The Dutch government wants to invest in more high quality services at places where they are needed most (Rijksoverheid, 2019). It is essential that the suitable services are selected prior to the investments. Selection of services can only be done by predicting loads on transit services. For these reasons, a realistic way of forecasting loads on public transport services is very important.

In the real world, public transport (PT) and everything that has to do with it, are very complex processes. Models are useful to make abstractions or idealisations of the real world. The best models use a balanced combination of fast and easy calculations and accurate results. The choice of transport mode, the travel time or the amount of passengers, can be computed with the use of certain models. Since these outputs all depend on large amounts of variables, it is hard to calculate them without a model that simplifies the real world.

Loads on transit lines are determined by predicting the routes and modes of transport that are chosen by travellers between a certain origin to destination pair (OD-pair). This helps at creating new timetables and high quality PT networks (Guis & Nijënstein, 2015). This information can also be used to make better models for PT services. The process of forecasting the users of a route between origin and destination (O and D) is called the transit route assignment. There are two main approaches of the transit assignment: frequency based and schedule based (Liu, Bunker, & Ferreira, 2010). Predicting the usage of a transit line is based on the characteristics of that certain line. These characteristics are called the skims.

The frequency based (FB) approach can be seen as a static transit assignment. Static assignments are characterised by the lack of temporal components. The schedule based (SB) method is a within-day dynamic transit assignment which incorporates temporal aspects. In general, the FB method makes use of frequencies of transit lines and the SB approach makes use of timetable information of transit lines. FB is a more simplified method and is therefore faster to use, however, as with most simplifications, this has some limitations with respect to detailed calculations. The SB method requires more detailed input and gives more detailed results, this makes the SB method more time-consuming. (Liu, Bunker, & Ferreira, 2010)

Despite the limitations of the FB algorithm this method is still the standard for the transit network assignment. FB models are less expensive to construct and take much less computing time compared to SB methods. FB methods do not require segmentations of OD matrices or any simulation of a timetable. (Cascetta & Coppola, 2016)

From a theoretical perspective, the SB method has more benefits. However, practical applications are limited, therefore the practical benefits compared to the regular methods are unknown. Benefits of the SB method do not outbalance the FB method in many cases, according to the users of the FB method. A SB approach might be able to improve results significantly. The advantages that a SB method provides, compared to the disadvantages it has, must become clear in order to facilitate the application of the method.

1.2 LITERATURE REVIEW

In this review, the differences and (dis)advantages of the schedule based assignment according to the literature are reviewed.

The FB method has more disadvantages in theoretical sense than it has advantages in practical sense. The practical advantages for this method are primarily focussed on the run-time and costs, which are both relatively low. Within a complex PT network it is more easy and faster to use a FB approach. In general, FB approaches are useful when high levels of detail are not necessary according to (Nuzzolo, Transit Path Choice and Assignment Model Approaches, 2007). This characteristic of the FB approach is also a shortcoming. Since there are differences in amounts of passengers during the day and within hours, dynamic time components become very important. During rush hours, there are peaks of travellers, which are dynamic and cannot be seen as static processes. A static approach as in the frequency method can cause overestimation or underestimation of intensities. Summarised the dynamic time component is lacking in the FB approach.

The FB way of assigning travellers is not satisfactory for many uses. For operational planning purposes, time dependent characteristics of the demand or the PT routes are needed to come to accurate outputs. Therefore, the SB approach is used to overcome these shortcomings. (Nuzzolo & Crisalli, The schedule-based modeling of transportation systems: recent developments, 2009)

Another shortcoming of the FB approach is that it is only possible to calculate average results (Nuzzolo, Transit Path Choice and Assignment Model Approaches, 2007). The calculation of waiting times can be largely overestimated with this approach. According to (Cascetta & Coppola, 2016) the FB method gives large over or underestimations when departure times are unevenly spread. Changes on the schedule have much larger effect on the over or underestimation of FB results than changes in the spread of demand.

An important difference lies within the processing of both algorithms. The SB algorithm models a more comprehensive representation of the transit network; this level of detail is harder to process compared to the FB approach. SB algorithms also require more detailed inputs. Origin-destination matrices must be created at a more detailed time level. (Veitch & Cook, 2013)

The main difference between both approaches is the way that transit services are treated. With the FB method services are considered as sets of runs. With the SB approach all runs of a transit service are considered individually. According to (Nuzzolo, Transit Path Choice and Assignment Model Approaches, 2007), FB can be seen as line based modelling and SB as run based modelling.

According to (Akse, 2016) there is a modelling problem that occurs with the FB method. This problem occurs when an infrequent, faster transit line is added to a route that already has a more frequent slower connection. In this case, the average generalised costs to go from O to D on this route, will become higher than it was, before the fast, infrequent line was added. This is remarkable, since an extra faster, but infrequent transit line would benefit the accessibility instead of being disadvantageous. It appears that this modelling problem for the FB method occurs quite often. In the SB method used in (Guis & Nijënstein, 2015) part of this modelling problem is bypassed. In this method they make use of the rooftop method instead of using a logit model. With the rooftop model inferior options are neglected, with the logit model all options get a percentage of travellers.

A large disadvantage of the SB method is the longer run-time compared to the FB method. According to (Wilson & Nuzzolo, 2004) and (Friedrich, Hofsäß, & Wekeck, 2001) SB algorithms have very long run-times compared to FB algorithms. This is an advantage of the FB algorithm.

Most applications of SB approaches are within transit networks, more specifically in areas where the use of the FB approach causes large approximations. For low frequent services, interchanges and departure times are very important to model. This can be done more easily with a SB approach.

Schedule-based algorithms are able to model competition between runs of the same service (e.g. intercity trains). This creates new options to look better into differences in usage of different services. (Nuzzolo & Crisalli, The schedule-based modeling of transportation systems: recent developments, 2009)

According to (Wilson & Nuzzolo, 2004) the SB method has been constructed for low frequency services. With high frequency services (average headways up to 15 min), it does not matter at what time a person arrives, since a transit service is departing very frequently. The SB approach is the most appropriate method when detailed values for PT service frequency, transfer time and vehicle loads are needed according to (Friedrich, Hofsäß, & Wekeck, 2001). However, there have been applications of SB methods for high frequency networks. In the paper of (Poon, Tong, & Wong, 2004) a SB model was used in the transit network of Hong Kong. In this study, the method was also validated with real world data.

FB assignments and static assignments in general, assume a constant demand over the observed time period. This makes it hard to discover bottlenecks in a network, since these are commonly caused by peak demands. For this reason, FB methods are not useful for problem solving in PT management. However, they can be useful for long term strategic planning purposes. (Liu, Bunker, & Ferreira, 2010)

There are some new developments that try to close the gap between SB and FB methods. The dynamic FB method by (Schmöcker, Bell, & Kurauchi, 2008), is able to model capacity constraints and a temporal effect. Using a "fail-to-board" probability the capacity constraint is modelled. Small time intervals are used and trips that take longer are carried out to the subsequent time interval.

There are also much more static approaches, which make use of an all-or-noting principle. For all-or-nothing methods all travellers between O and D will make use of the most optimal route. Inferior routes are neglected in this way of assigning. No information about route choice behaviour is gathered with these methods. More passenger oriented approaches give a better representation of reality. (Liu, Bunker, & Ferreira, 2010)

In the table below (Table 1) usage in different situations, according to literature, is described.

Table 1: Differences between methods

	Frequency Based	**Schedule Based**	**Source**
Detailed modelling	Not suitable for modelling high details.	Better at deriving more detailed results.	(Nuzzolo, Transit Path Choice and Assignment Model Approaches, 2007)
Fast calculations	Better at getting fast model calculations.	Not suitable for fast calculations.	(Cascetta & Coppola, 2016)
Low cost modelling	Relatively lower costs to build a model.	Relatively higher costs to build a model.	(Cascetta & Coppola, 2016)
Low frequency networks	Can give large under or over estimations with low frequency networks.	Very suitable for usage within low frequency networks.	(Wilson & Nuzzolo, 2004)
High frequency networks	Suitable for modelling high frequency networks.	Less suitable for high frequency networks.	(Wilson & Nuzzolo, 2004)

Much fluctuating demands	Cannot cope with fluctuating demands.	Very useful when demand fluctuate very much.	(Cascetta & Coppola, 2016)
Unevenly spaced departure times	Not suitable when departure times are unevenly spread over time.	Very useful when departure times are spread unevenly.	(Cascetta & Coppola, 2016)
Model competition between runs	Cannot model competition between runs since in only looks at sets of runs.	Very useful when competition between runs has to be modelled.	(Nuzzolo & Crisalli, The schedule-based modeling of transportation systems: recent developments, 2009)
Little input data available	Useful when there is a lack of data available.	Not useful since it is required to have much input data.	(Veitch & Cook, 2013)
Long term planning	Less data available of future transit services. Therefore it is very useful.	Less data available of future transit services. Therefore it is not very useful.	(Liu, Bunker, & Ferreira, 2010)
Congested network	Less useful, since it is not able to model individual runs.	It is able to differentiate between runs, so it is very useful.	(Schmöcker, Bell, & Kurauchi, 2008)

1.3 PROBLEM AND RELEVANCE

From the literature it becomes clear that there is a lot of understanding in the improvements a SB approach can provide in theoretical sense. The disadvantages of the SB approach in theoretical sense are also known. In practice, the FB method is still preferred. This preference of the FB method, might be caused by the fact that not much is known about the improvements a SB method brings in practice and if this outweighs the pros of the FB method. Current literature lacks at giving a clear practical comparison between schedule and frequency based approaches. It is not known how large the improvements are and to what extend certain situations need to be modelled with schedule based methods.

The most important disadvantage of the SB method is the costs and performance. The performance depends directly on the detail level that is used in the calculation. The detail level in the SB method can be changed to improve or decrease performance. The perfect balance between a good performance and detailed results in a practical sense is something that does not come forward from the literature.

There is a lack of knowledge about the benefits a SB approach has in practice. This is very important to overcome since there is a demand for the use of a SB approach. Goudappel Coffeng urges to make use of a SB approach in the future. In addition, other public transportation companies have indicated that they would be interested receiving data from a SB method.

1.4 RESEARCH AIM

To solve the problem, the SB algorithm should be tested and compared with the FB algorithm. The results will have to be compared and explained to gain more insights about the functioning of the algorithm. This study must: give more insights in the SB algorithm, facilitate the use of this method and gain more knowledge about the benefits of the SB method compared to the disadvantages. A recommendation in the usage of both methods should also be given. The main research question is: *What are the main differences between the schedule based and frequency based methods in a practical* *application and what influences these differences?* To achieve this aim the following sub-questions are formulated:

I. What are the main practical differences between both methods?
   a. What are the differences in input?
   b. What are the differences in run-time?
   c. What are the differences in results?
II. How do the skims of the SB algorithm compare to results from the FB algorithm?
   a. How do these results behave in different situations?
   b. Which algorithm gives results closer to the ground-truth data?
   c. Are these differences logical?
III. What is the influence of different parameters of the SB algorithm?
   a. What parameters have large influence?
   b. What parameters have the lowest cost benefit ratio?

1.5 Research Lay-out

In this section the lay-out of this research is described. The study consists of two main parts: an in-depth description of both assignment methods using available literature and a case study done on the Dutch rail network. These main parts are used to reach the aim of this research.

The in-depth description of both methods consists of: an introduction to route assignments, theoretical description of both algorithms and a practical description and application of both methods. More understanding in both methods is gained, by this methodology description. It has to become clear what the main inputs and outputs are. With this information, the first sub-question can be partly answered. This answer is needed to make an application of the assignment methods on the case network possible.

Next, a case is study is done. First, the model and data used in the study is introduced. Then all analysis methods are described, which are used to analyse results of the case network. The case study consists of two main analysis steps. The steps are used to answer the last two sub-research questions. The first step consists of comparing skim results of both algorithms. Subsequently, the third step will be a sensitivity analysis, which gains insights in the results when certain settings are changed. Run-times will also be noted to complete the answer to sub-question one. The steps can be seen in the figure below (Figure 2) and how they contribute to the final goal.

Results of the case study are analysed in the fourth section. From these results and in combination with the theory all research questions can be answered. In the end, the study is discussed and a recommendation is given. In the appendices some tables and graphs are given which can be used to get some more in-depth understanding in the study.

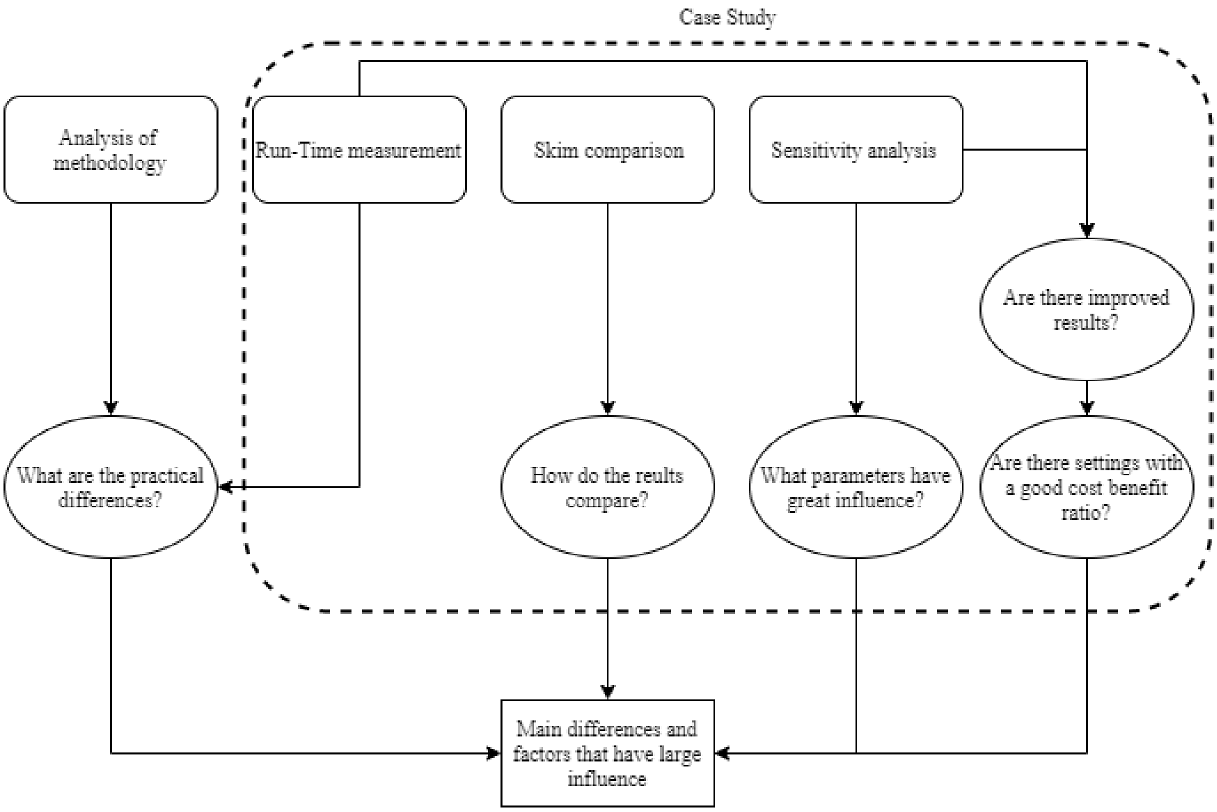

Figure 2: Lay-Out of the Research

2 METHODOLOGY OF ASSIGNMENT METHODS

In this chapter the methodology of the transit route assignment is given, this helps to get more understanding in the topic. Fist some theory about forecasting loads on PT is given. Next, both methods are described in full detail.

2.1 PUBLIC TRANSPORT MODELLING

Transit route assignments are carried out on a network. Networks must contain all possible origins, destinations and the route options between them. A passenger transportation network is a graph with nodes and links. In the network links are used to model transit lines. Nodes are used to model stops or stations. Centroids can be considered as origins and destinations. All centroids contain data of the destination of travellers. This data is called demand data, it can be found in an OD-matrix. The OD-matrix shows for every centroid the passengers that want to go to any other centroid. To get from the origin centroid to the closest stop at which the transit service can be boarded, an access mode has to be used. To get from the last stop to the destination centroid, an egress mode has to be used. Egress or access modes can be car, bike or walk. An example of a network can be found in Figure 3.

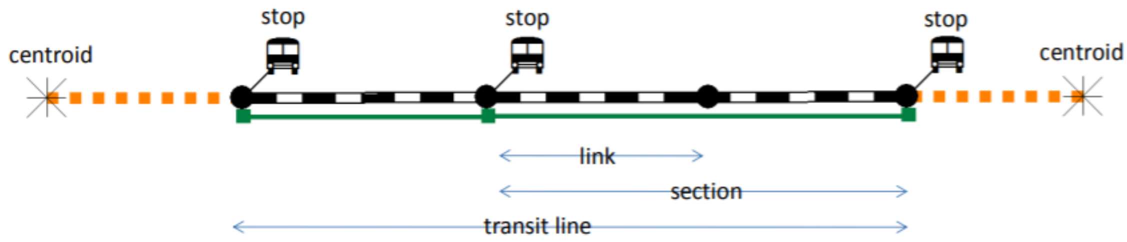

Figure 3: Network with one transit line and three stops (Brands, Romphc, Veitche, & Cook, 2014)

The route assignment, which calculates the proportions of passengers of a route, is part of a four-step model for PT modelling. This model is shown below (Figure 4). The four step model is used to predict the behaviour of travellers. In the first step, trips from every centroid in the network are determined. In the next step, the amount of trips between O and D centroids are calculated. The mode choice determines the mode that a traveller is going to use. In the PT network assignment multiple modes are used, therefore trip mode chains are used (e.g. walk – train – car). The step which is most important in this research and the last step of the 4 step model, is the route assignment. In this step the route between the origin and the destination are determined. A loop can be seen in Figure 4, this is used for iterations. The iterations are done using skims, these are matrices consisting of characteristics of an OD-pair: distance, travel times, costs or a combination of those factors (generalised costs), for each OD-pair (Travel Forecasting Resource, 2019).

The figure below (Figure 4) shows how skims influence trip distribution and mode choice, therefore accurate calculation of skims is very important. Variables of each route are skimmed from the network and put into the skim matrices. When skim calculation of routes is done accurately, it positively influences the entire model. The main part of the skims that determines if a transit service is used is the generalised costs. Generalised costs is a concept that was developed to get one variable that contains all other variables. Generalised cost can be explained as the weighted sum of all variables of a route (Transportmoddeler, 2019). Variables of a route are: travel time, waiting time and number of transfers.

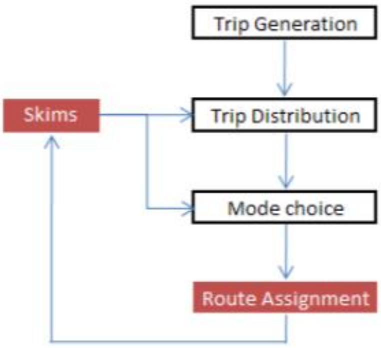

Figure 4: Four-step model (Veitch & Cook, 2013)

The general scheme of an assignment model in transit modelling can be seen in Figure 5. This scheme consists of a supply, path choice and an supply-demand interaction model. The supply demand and interaction model can be seen as the transit route assignment. As mentioned earlier the two main methods for this are FB and SB. Regularity and information characteristics are gathered by using intelligent transport systems (ITS). This consists of advanced PT systems (APTS) and advances traveller information systems (ATIS). (Nuzzolo, Transit Path Choice and Assignment Model Approaches, 2007)

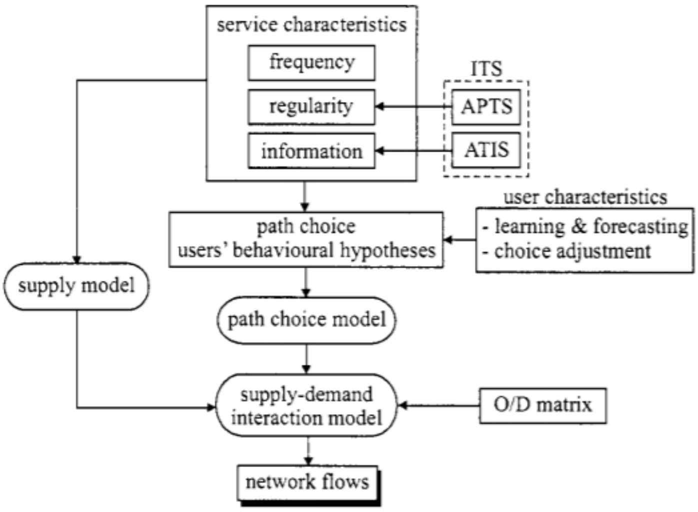

Figure 5: General scheme of transit assignment models (Nuzzolo, Transit Path Choice and Assignment Model Approaches, 2007)

For this study specifically, train connections are analysed. Most of these intercity, suburban or regional train connections belong to low frequency services (average headways of 15 min or more). Characteristic for these services, is the assumption that travellers have all information necessary before boarding any transit service. This means that choices about stop and run are made before the trip. Transit services that have a low frequency are also assumed to be uncongested systems. This implies that factors like: vehicle capacity, day-to-day dynamics and the problems that occur with these factors, are not taken into account. (Nuzzolo & Crisalli, The schedule-based modeling of transportation systems: recent developments, 2009)

The attractiveness of routes is determined with the data in the skim matrix. Attractiveness of a route depends on several factors. Less travel time results in more qualitative time-use; less travel time makes a route more attractive. Transfers also have a huge effect on attractiveness of a route. The less transfers, the more likely a route will be used. Quality of these transfer also matters. Transfer time may not be too long, since this takes up more time, but it can also not be too short, since this results in more missed connections. The distance a traveller has to walk to the connecting train also determines quality of a transfer. The period in which a transit service departs is also important for the attractiveness of a route. If the transit service departs in the time frame at which the traveller wants to depart, it makes this transit service more attractive. The last factor of attractiveness is the delay that a traveller obtains if it misses the connection. (Guis & Nijënstein, 2015)

2.2 ALGORITHM DESCRIPTION

In this part the algorithms used to conduct a frequency or schedule based assignment are described. The methodology of the OmniTRANS assigning method will be explained, specifically the OtTransit method. First, the theory of the algorithm is explained then the practical approach is described. The FB approach is based on (Veitch & Cook, 2013), (Brands, Romphc, Veitche, & Cook, 2014) and (Brands, Multi-objective Optimisation of Multimodal Passenger Transportation Networks, 2015). The SB approach is based on (Friedrich, Hofsäß, & Wekeck, 2001) and (Veitch & Cook, 2013). Both algorithms are implemented in the OmniTRANS software (DAT.Mobility, 2019).

2.2.1 Frequency Based algorithm

It is assumed that an individual traveller is going from an origin O to destination D with a certain mode of PT. This means that the modal split step of travellers has already been completed.

First the stops at which the transit service can be boarded is determined. This is depending on the access or egress mode. The access and egress modes are used to reach the boarding or alighting stop respectively. These modes can be bike, walk or car. For each destination or origin a group of stops is identified which can serve as the start of the PT route. How these stops are selected depends on the following factors:

- Distance radius
- Type of PT
- Type of stop
- Minimum number of stops

The set of stops that are available is bounded by these parameters. All stops that are selected for the destination or egress stop are possibilities for the final stop. The model that chooses the lines that can be used works in a reversed direction, from the egress stop to the access stop. For every stop on the line that has been identified, the generalised costs are calculated. These generalised costs are the costs to reach destination D, from the moment that the line has been boarded. This excludes the access mode and the waiting time but it includes the egress mode.

The generalised costs are a characteristic of a link in the route. The generalised costs consists of five parts: Travel Distance, Travel Time, Waiting time and Penalty Fare.

These can be calculated with formula 1.

$Clink = \alpha mTl + \beta mKl + \gamma mPl$ (1) (Brands, Romphc, Veitche, & Cook, 2014)

Where:

$Clink$	Generalized Link costs of a link
l	Link
Tl	On-board Travel time on a link
Kl	Fare costs of a link
Pl	Penalty for Transfer
$\alpha m, \beta m, \gamma m$	Scaling factors dependent of mode

When all generalised costs are calculated, these costs are summed up per route. These costs per route are the most important input to calculate the proportion of passengers that use the route. The probability to board the line is calculated with formula 2.

$$pl = \frac{F_l e^{-\lambda Cl}}{\sum_{x \in L} F_x e^{-\lambda Cl}}$$ (2) (Brands, Romphc, Veitche, & Cook, 2014)

Where:

Cl	Generalized costs of a line l
x	Any line from stop s reaching j
Fl	Frequency of line l
λ	Scaling (Logit) parameter
pl	Probability of boarding line l

Since there can be several transit lines at a stop the waiting time used is based on a combined frequency. The combined frequency (CF) is a trade-off between in-vehicle travel time and waiting time. The formula to calculate CF can be found below (formula 3).

$$CF_u = \sum_{l \in L_{um}} F_l \frac{e^{-\lambda C_{lu}}}{\max_{x \in L_{um}} e^{-\lambda C_{xu}}}$$ (3) (Brands, Multi-objective Optimisation of Multimodal Passenger Transportation Networks, 2015)

Where:

L_{um}	Subset of lines passing stop u
C_{lu}	Generalised costs of line l from stop u

To calculate the total costs to reach a destination from any origin in the network the formula below is used (formula 4).

$$TC_u = \min(MW, WT) + \sum_{l \in L_{um}} pl\ cl$$ (4)

Where:

TC_u	Total costs to reach a certain destination from stop u
MW	Maximum waiting time
WT	Waiting time translated from the combined frequency

2.2.2 Schedule Based Algorithm

In this report the focus will be on the line transit choice, rather than on the stop choice. Only the line choice part of the algorithm will be explained. The input of the algorithm is a temporal distribution of the travel demand between origin and destination (DEM). This temporal OD-matrix distribution is then further spread in equally divided time steps. These time steps define the moment at which travellers are placed on the network. If the time step gets smaller, the calculation gets more detailed and the computation time will be longer.

To obtain a set of routes that a traveller from O to D a branch and bound method is used. First all connection segments between O and D are determined. A route from O to D that is made up of a train that goes from O to T (transfer stop) and a train that goes from T to D, consists of two connection segments. Subsequently, the arrival and departure times of these connection segments are stored in a sorted array.

To determine all potential routes, a time dependent, multi path algorithm is used. User defined parameters are used to bound available routes, similar to the FB algorithm. These parameters are called the branch and bound parameters and can be used to make the route selection larger or smaller depending on the values. A smaller selection will result in lower computation time and less detailed results. The algorithm creates a connection tree (Figure 6), which contains all possible routes from O to D. From this tree, the paths are determined and are used in the choice of routes. The levels that can be seen in the figure represent the transfers in the path. The amount of transfers can be limited by setting the maximum interchange setting. In the example figure below, this limit has been set to four.

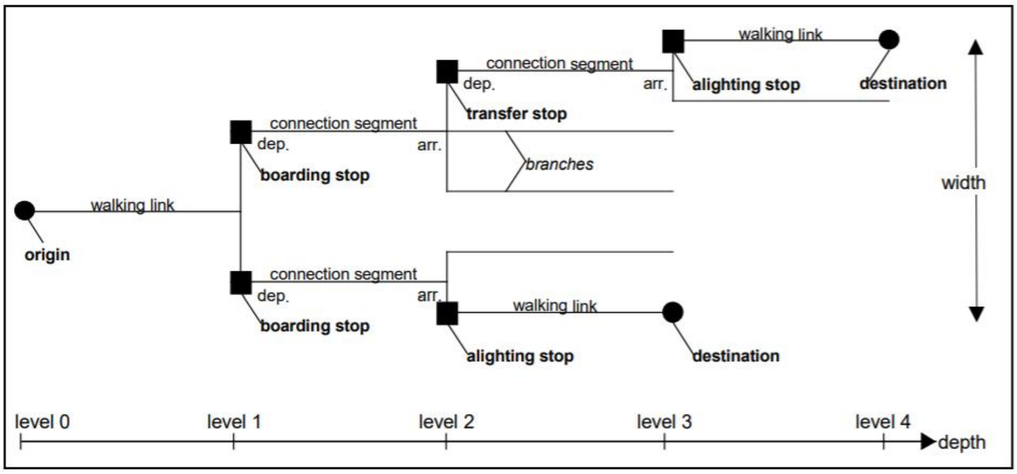

Figure 6: A Connection Tree (Friedrich, Hofsäß, & Wekeck, 2001)

It is assumed that travellers make their decision based on the generalised costs. These costs are a combination of the perceived journey time (PJT), the transit fare (FARE) and the difference between the real and preferred departure times. A way to calculate the PJT of a connection c is shown in formula 5. The generalised costs of connection c can be calculated with formula 6.

$$PJT_c = JT_c + 2\,TT_c + 2\,NT_c \qquad (5)\ \text{(Friedrich, Hofsäß, \& Wekeck, 2001)}$$

$$C_c = q_1\,PJT_c + q_2\,U_{c\,(a)} + q_3\,FARE_c \qquad (6)\ \text{(Friedrich, Hofsäß, \& Wekeck, 2001)}$$

Where:

$U_{c\,(a)}$	Temporal utility for travellers departing in time interval a
$q_{1,2,3}$	User set constants
JT_c	Journey time
PJT_c	Perceived journey time
TT_c	Transfer time
NT_c	Number of transfers

The temporal utility shows the difference between a passengers real and preferred departure time. When the connection departs within time interval a, $U_{c\,(a)}$ will be zero. If the connection departs at another time U will increase monotonously. U cannot become negative, since travellers cannot depart before their preferred departure time interval.

The proportion of travellers using a connection is calculated with a utility function, which takes into account the 'independence' of a connection. Independence of transit lines is defined as the amount of difference between two transit lines. The difference is based on departure and arrival time, perceived journey time and fares. Formula 7 is used to calculate the independence of a connection c, which is part of subset C ($c \in C$).

$$IND_c = \frac{1}{\sum_{c' \in C} f_{c(c')}} = \frac{1}{1 + \sum_{c' \neq c} f_{c(c')}} \qquad (7)\ \text{(Friedrich, Hofsäß, \& Wekeck, 2001)}$$

$$f_{c(c')} = \left(1 - \frac{x_{c(c')}}{s_x}\right) \times \left(1 - \gamma \times min\left\{1, \frac{s_z\,|y_{c\,(c')}| + s_y\,|z_{c(c')}|}{s_y\,s_z}\right\}\right) \qquad (8)$$

$$x_{c(c')} = \frac{(|DEP_c - DEP_{c'}| + |ARR_c - ARR_{c'}|)}{2} \quad (9)$$

$$y_{c(c')} = PJT_{c'} - PJT_c \quad (10)$$

$$z_{c(c')} = FARE_{c'} - FARE_c \quad (11)$$

Where:

f_c	An non-negative evaluation function
$x_{c(c')}$	Temporal similarity of connection c
$y_{c(c')}$	The advantage of connection c considering PJT
$z_{c(c')}$	The advantage of connection c considering FARE
$s_{x,y,z}$	Determine the range of influence for the three variables
γ	Global parameter
DEP	Departure time
ARR	Arrival time

The evaluation function gives penalties to connections with departure times that are close to each other. This means that connections that are identical or have similar departure times are assigned a low 'independence'. Goal of the function is to spread travellers realistically over all different connections. Connections that are similar or identical attract passengers from the same group, which results in lower usage, whereas connections that are unique also attract passengers from a unique group.

The last factor that is necessary to compute the proportion of passengers on a certain connection is a Box-Cox transformation, which is calculated with formula 12.

$$b^t(C_{(c)}) = \begin{cases} \frac{C_{(c)}{}^t - 1}{t} & if\ t \neq 0 \\ \log(C_{(c)}) & if\ t = 0 \end{cases}$$ (12) (Friedrich, Hofsäß, & Wekeck, 2001)

Where:

$b^t(C_{(c)})$	Box-Cox transformation of generalised costs of route c

Now the proportion of passengers on each connection can be calculated, this is done with formula 13.

$$P_{a(c)} = \frac{e^{-\beta \cdot b^t(C_c)} \cdot IND_c}{\sum_{c' \in C}\left(e^{-\beta \cdot b^t(C_c)} \cdot IND_c\right)} \cdot DEM_{(a)}$$ (13) (Friedrich, Hofsäß, & Wekeck, 2001)

Where:

$P_{a(c)}$	Proportion of passengers on route option c from stop a
β	Logit parameter
$DEM_{(a)}$	Demand for access stop a

This makes it easier to show the effect of the concept of independence. Assume a scenario in which $DEM_{(a)}$ = 100. These 100 passengers can make use of a few connection between a = [08:00, 09:00]. All transit connections depart within a, therefore the assumption is made that $U_{a\,(c)}$ = 0. To make it easier q_1 and $q_{2,3}$ are assumed to be 1 and 0 respectively. f_c is used as evaluation function. To get the standard Kirchhoff distribution, β and t are assumed to be 2 and 0 respectively.

An example of the results gained using the concept of independence is seen below (Table 2). As can be seen the independence has no effect on a symmetrical schedule.

Table 2: Connection split: three connections with fixed headway (Friedrich, Hofsäß, & Wekeck, 2001)

c	DEP(c)	PJT(c)	IND(c)	Pa(c) not using IND(c)	Pa(c) using IND(c)
1	08:15	20 min	1,00	33	33
2	08:30	20 min	1,00	33	33
3	08:45	20 min	1,00	33	33

A second example is shown below (Table 3). In this example, it becomes clear that identical connection get the same proportion by using the independence.

Table 3: Connection split: adding an identical connection (Friedrich, Hofsäß, & Wekeck, 2001)

c	DEP(c)	PJT(c)	IND(c)	Pa(c) not using IND(c)	Pa(c) using IND(c)
1	08:15	20 min	1,00	25	33
2	08:30	20 min	0,50	25	16,5
3	08:30	20 min	0,50	25	16,5
4	08:45	20 min	1,00	25	33

Another example shows the effect of the insertion of a fast connection (Table 4). As can be seen from the table, the fast connection only has a small effect on the first connection, since it departs much later than connection one. The fast connection departs close to connections two and four, therefore it detracts more passengers from these connections.

Table 4: Connection split: adding an fast connection (Friedrich, Hofsäß, & Wekeck, 2001)

c	DEP(c)	PJT(c)	IND(c)	Pa(c) not using IND(c)	Pa(c) using IND(c)
1	08:15	20 min	1,00	21	23
2	08:30	20 min	0,86	21	19
3	08:40	15 min	0,94	37	39
4	08:45	20 min	0,86	21	19

2.3 APPLICATION OF ALGORITHMS

In this part the practical approach is described. To start with, the settings and parameters are explained. Subsequently, a case is used to describe the methodology of both methods.

2.3.1 Logit parameter

The logit parameter has to be defined for both methods and is used to control the difference between less optimal and optimal routes. A high logit parameter value means that a larger proportion of the travellers make use of the most optimal route option. If it becomes smaller a larger proportion uses the less optimal routes. This process is shown in Figure 7. Line A is the most optimal line and line B is a less optimal line. In reality these very low logit values are never used, since sub-optimal routes are never preferred over optimal routes.

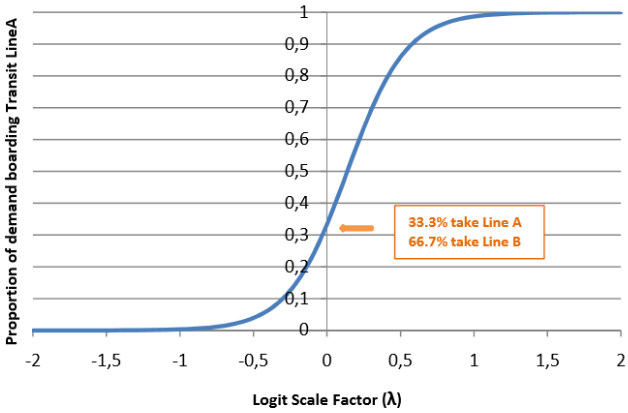

Figure 7: Effect of logit scaling parameter (Veitch & Cook, 2013)

2.3.2 Frequency Based configuration

Since demand varies during the day, FB assignments are done over a certain time period (e.g. morning rush hour). The OD demand matrix of this specific time period is then used in the assignment.

Bounding settings are used to determine maximum skim values, to prevent the methods from computing unrealistic skim values. For the FB method the maximum access waiting time and maximum transfer waiting time can be defined. These settings are used to prevent extreme unrealistic waiting times at low frequencies. The maximum transfer waiting time also makes it possible to model short transfer times, which were otherwise impossible.

2.3.3 Schedule Based configuration

Level of detail can be controlled to keep control of computation times. Time step and route choice set size can have great influence on the computation times. Size of time steps determines the smallest level of time that the SB method is able to differentiate in. A smaller differentiation level means more detailed modelling, but also more computation time. Size of route choice set determines the amount of possible routes options between O and D. Large sets of routes mean a lot of possibilities and therefore higher details and more computation time. It is possible to ignore certain unlikely route options in the route choice set to improve computation times.

It is possible to limit the route choice set in the SB assignment by using branch and bound parameters. There are three branch and bound parameters: cost limit, travel time limit and transfer limit. The cost limit and travel time limit parameters are used to define the maximum relative difference that a route option is allowed to have, compared to the most optimal solution. Assume a scenario where the cost limit parameter is set to 1,3. In this scenario, route options are only accepted if it costs less than 1,3 times the cost of the most optimal solution. The transfer limit parameter defines the maximum absolute difference in transfers, compared to the most optimal solution.

For the SB method it is also possible to set a limit on the access waiting time and the transfer waiting time. Since passengers want to depart in their designated timeframe, only routes within a defined time frame are selected using the maximum access waiting time setting. In a scenario where the person wants to leave only 30 minutes after its desired departure time, only routes within that timeframe are considered. For example, if the person wants to leave at 07:00, only routes that before 07:30 are considered. It does not matter if the routes within that time interval are less optimal. If the algorithm is not able to find any route that meets all settings and is within the desired time period, travellers are moved to the subsequent time step. The maximum interchange waiting time setting limits possible routes to a certain maximum transfer wait time.

The SB method can also be influenced by other time periods. Simulated time periods are influenced by the time periods before. Travellers from another time period might use transit connections inside the simulated time period. This also happens for the period after the simulated period. Travellers from the simulated time period might use transit connections outside the that period. Influences like these have to be taken into account to keep modelling realistic. The problem is solved by using warmup and cooldown periods.

2.3.4 Application

Assume a scenario in which a group of travellers arrive at station A between 07:20 and 07:25 and want to travel to B. For this route there are two options that are logical to use, the options can be found in the table below (Table 5).

Table 5: Options for a single time slot

Option	Type	Departure time	Average Access Waiting Time (minutes)	In-vehicle Time (minutes)
Option 1	Sprinter	07:24	0	68
Option 2	Intercity	07:46	25	57

When running a SB assignment the outcome is that 50% of the travellers use the sprinter connection and the other 50% uses the intercity connection. The calculated skim value for travel time of the simulated time slot is 62,5 minutes, this is the result of this assignment.

It is possible to see the proportion of travellers per route option. For the FB method, it is only possible to differentiate between route types, not between runs. To get the same result from the FB assignment the skim values have to be examined. From skim matrices, it can be concluded that the Intercity connection is used approximately 65% and the Sprinter 35%. However, these proportions are calculated using a load for the entire morning rush hour period (07:00 – 09:00), unlike the single time slot that is used for the SB assignment. The FB method is also not able to simulate a single small time slot.

To model a larger period like in the FB approach for the SB method the simulation period has to be larger. The simulation time needs to contain all possible options to create the most realistic simulation. The simulation time is one hour. The same origin-destination pair will be simulated, but now with passengers departing at every time between 07:00 and 08:00. The time step setting is still set to five minutes. This will result in 12 time steps of five minutes. In each time step an equal amount of passengers are put on the network.

Assume that a group of travellers arrive at station A between 07:00 and 08:00 and want to travel to B. All logical options are shown below (Table 6).

Table 6: Options for assignment over entire hour

Option	Type	Departure time	Average Access Waiting Time (minutes)	In-vehicle Time (minutes)
Option 1	Intercity	07:16	8	57
Option 2	Sprinter	07:24	12	68
Option 3	Intercity	07:46	15	57
Option 4	Sprinter	07:54	15	68
Option 5	Intercity	08:16	23	57
Option 6	Sprinter	08:24	27	68

Waiting times are determined as an average over the time steps. This is due to the fact that for every time step a skim value for waiting time is calculated. These waiting times are an average for all time steps between the departure time of this specific train and the departure time of the last train of the same type.

From the simulation it can be seen that only 9% uses the sprinter to reach the destination , 92% of the travellers use the Intercity train. Since the SB method provides the option to differentiate between different options it is also possible to see the proportions of every option mentioned above. This result is visible in Table 7.

Table 7: Results for SB assignment

Option	Type	Proportion
Option 1	Intercity	33%
Option 2	Sprinter	4%
Option 3	Intercity	46%
Option 4	Sprinter	5%
Option 5	Intercity	12%
Option 6	Sprinter	0%

The proportions that are calculated are used to determine the skim values of every route. This means, for example, that the total in-vehicle travel time is a weighted average based of the proportions from the assignment. For this SB example that comes down to approximately 58 minutes. In-vehicle travel time is approximately 61 minutes with a FB method. As can be seen from these values there is a difference between the values. The different approach causes that these two values are different.

3 CASE STUDY

In this chapter the case study used to gain results is described. First, the model and data used in the case study is described. Subsequently, the analysis methods are described.

3.1 DUTCH NATIONAL RAIL MODEL

The first step of the research involves gathering data to work with. The most important model that is used is the Dutch National Rail Model, further revered to as National Rail Model. This is a network of all train lines and stations in the Netherlands in 2013. An overview of the network can be seen in the figure below (Figure 8). Within this network, all input variables for: schedule, frequency and demand, are already defined. Timetables and frequencies correspond with the real schedule at that time. The network has 402 centroids, which can be seen as stations. Each station can be seen as origin or destination, therefore there are 161.608 OD-pairs. All used data from the network also consists of 161.608 data points. OD demand data is calibrated from the station exit and entry data, which is derived from (Treinreiziger.nl, 2019), the structure is based on the national model from 2008. Demand data is separated in three time periods: morning rush hour, evening rush hour and 'rest day'. The software that is used to run the models is OmniTRANS 8.0 (DAT.Mobility, 2019) this software is suitable for the simulation of low-frequency transit systems according to: (Nuzzolo & Crisalli, The schedule-based modeling of transportation systems: recent developments, 2009).

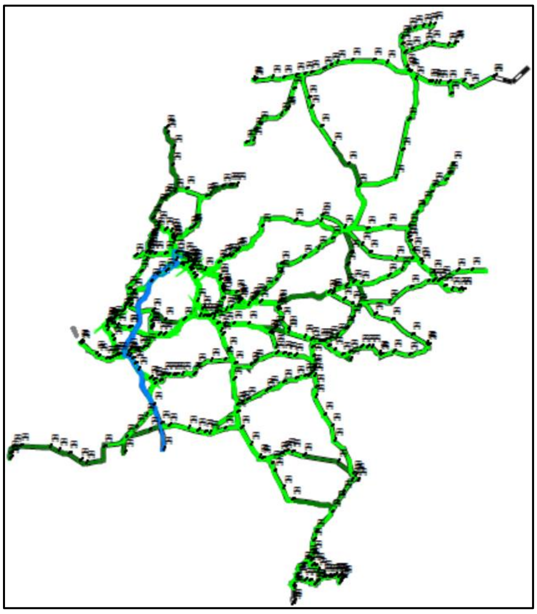

Figure 8: Overview of the National Rail Model

3.2 'REAL WORLD' DATA

Real world data from the train connections has also been gathered. This data consists of travel time, transits, transit time and distances between transits. This data has been gathered from an application of the Dutch Railways (NS, 2019) in which it is possible to plan trips by train this data will be from 2019. To obtain data from the application, choice of route has to be made beforehand, since it only shows travel times per route option. The choice has been made that only data from fastest route is obtained from the NS application.

3.3 SKIM GATHERING

Both methods are compared using skim matrices. These skim matrices consist of characteristics of each OD-pair. The skims can be separated in four categories: total route, access, in-vehicle and egress. For each category skims for travel time, waiting time and transfer penalty are used in the comparison. Skims are generated using both algorithms.

The assignments are done using both algorithms. Skims are generated per OD-pair. To make comparison possible, skims of both methods have to represent the same time period. The morning peak period between 07:00 and 09:00 is used. This means that the OD demand matrix, schedule and frequency of this time period is used in the assignment.

The SB assignment is done over a 60 minutes period: from 07:00 till 08:00. In the dutch rail network all lines depart at least once an hour, this means a 60 minute period includes all possible options. Demand fluctuation over the time period was not used, this was done to make comparison with FB data easier. Another reason to not implement demand fluctuation is that there is no information available to implement this. Since the demand fluctuation was disabled, the entire 60-minute period represents 100% of the demand in the morning rush hour. The 60 minute time period is spread in twelve, five minute time steps.

Maximum access and transfer waiting time for the FB assignments is set to 60 and 30 minutes respectively. For the SB assignment both were set to 30 minutes. The FB assignment works with average waiting times, therefore the SB and FB limits give comparable results with these settings.

The logit parameter value that is used is 0,6. This parameter is based on earlier studies carried out at Goudappel Coffeng. This setting of the logit parameter is used for both methods. Some travellers make use of sub-optimal routes, but the most travellers still make use of the most optimal route with this logit value.

In order to compare the FB skim matrices with the SB skim matrices the unit has to be equal. Skim results for the SB method are built for every time step. In a standard situation, every OD-pair has skims for every time period. For the FB method, results are an average of the whole assignment period. Therefore the skims of all time periods of the SB method have to averaged. With the average results of the SB assignment it is possible to compare with FB skim results.

During the skim generation it also became clear that for some relations only a few time steps had useful results. When the algorithm is not able to find any route within that time step, the skim results are not useful anymore. Useless skims are called 'disconnected' skims and useful skims are called 'connected' skims. There can be multiple reasons for these disconnected skims. It is possible that no route can be found within the maximum access waiting time. Another possibility is that there are only routes available with a transfer wait time higher than the maximum allowed transfer wait time. An average of the SB skims can only be created when these skims are filtered out of the data. In the normal situation, all time steps are considered in averaging the skims, in reality only the connected skims were used in the calculation.

A minimal amount of connected skims is defined, to prevent OD-pairs with very little useful skim results to influence the results. If the OD-pair has less than this number of useful skims, the entire relation is not used in the comparison. The minimal amount of skims is set to six. This means that, within at least six time steps, a route can be found. Since the lowest frequency in the National Rail Model is once every hour, any route should be available within 30 minute (six time steps) of waiting time. For this reason, OD-pairs with less than six skims are considered unreliable.

3.4 SKIM COMPARISON

This method is used to answer the following sub question: *How do the skims of the SB algorithm compare to results from the FB algorithm?* To answer this question skim results of both algorithms are compared. Skim matrices of travel time, waiting time and penalty are used in the comparison. The skim data is analysed both in-depth and quantitatively.

3.4.1 Quantitative analysis

The quantitative analysis and comparison is done using the entire skim matrix. This means that all relations are considered, unless they do not meet the minimum skim number. Generated skim matrices from the FB assignment are subtracted from the SB skims. The median is used in this case, instead of the average, to filter out all extreme results. This median difference is then used to make histograms. These histograms help to create a better overview of the large data set. Skims types that are analysed are: in-vehicle travel time, total travel time, total waiting time, access waiting time, transfer waiting time and penalties.

It is also valuable to know if important relations behave as expected. Important relations are defined as relations that have large demands. The in-vehicle travel times are compared with the demand matrix to verify if the method gives reliable results for important relations. A scatter plot is made to show to what extend high demand relations have high deviations.

The next analysis that will be done is a characteristics based analysis. OD-relation skim values are divided based on their characteristics. Characteristics that are used in the comparison are distance and number of transfers. OD-relations are put into groups with the same characteristics, however, only if they meet the characteristics for both the SB and FB assignment results. Median values from the groups are put into a graph and are then used to analyse the results. The focus will be on finding correlations between certain situations. These situations are important since it makes clear in what situations which method is better to use.

3.4.2 In-depth analysis

An in-depth analysis is done for some random OD relations with specific characteristics. These relations are handpicked from the network. For every unique situation a few relations are observed. These situations are: high frequency, low frequency, no-transfer, with transfer, alternating (transfer/no-transfer), short distance and long distance. The alternating situation exists when a path between O and D differs over time. This means that at some time in the hour a direct connection to the destination is possible and at another time a transfer is required.

Travel time, waiting time and penalty skim data of both algorithms is used in the analysis. The skim values that have been gathered from the real world network, are also used to check if they correspond with reality. This is done by using the real world travel time data from the NS application. The differences in certain situations are then logically explained. An analysis like this creates more in-depth understanding of the benefits of the SB method.

3.5 SENSITIVITY ANALYSIS

Influence of parameters has to be known to answer the question: *What is the influence of different parameters of the SB algorithm?* There are several parameters that are used specifically for the SB assignment, these parameters are used in an sensitivity analysis. A sensitivity analysis is able to analyse the effects of certain parameters. The key performance indicators (KPIs) that are used in the sensitivity analysis are: total travel time, travel time difference and number of connected skims. To find out what parameter settings can be used ideally in future assignments the run-times of parameters, run-times are also measured. Therefore, parameters that are ideal to test, are the ones that influence the detail level, therefore also the run-time, directly.

Parameters that are tested need to be specific for a SB assignment and influence the detail level. Parameters that meet these requirements are: time step size, branch and bound, maximum number of transfers and maximum access waiting time. Since the effect of disconnected skims is also something which can have large influences, this parameter is also tested.

In the table below (Table 8), the branch and bound parameters that are used in the sensitivity analysis are shown. As already mentioned, the branch and bound parameters define the routes that can be used by the travellers between O and D. Strict settings only allow routes that are slightly less optimal than the most optimal route between O and D. Loose settings allow very sub-optimal routes to be used. The loose extra settings also allows routes with two extra transfers.

Table 8: Branch and Bound Settings

Settings Name	Allowed extra costs	Allowed extra time	Allowed nr. of extra transfers
Strict	10%	20%	1
Middle	20%	30%	1
Loose	30%	50%	1
Loose Extra	30%	50%	2

All settings, for every sensitivity analysis that is performed, can be found in Table 9. The parameter settings for times step size are changed from high detailed, small steps, to lower detailed, larger steps. Maximum number of transfer settings are changed from a very low limit, to a very high limit. The low limit only allows routes with a two transfers and the high limit allows routes with a large amount of transfers. The settings for maximum access waiting time are changed from a very low waiting time, to a very high waiting time. Only short access waiting times are allowed for low access waiting time settings and long waiting times for high access waiting time settings. Minimum number of skims settings are changed from a low limit to a high limit. A low limit considers all OD-pairs with at least one useful skim. High limit settings only consider the OD-pairs of which all skims are useful.

For each calculation in the sensitivity analysis, computation time is noted. When the skims are generated, the improvements in skim results are determined. In this way, the pros (more detailed results) of the SB method are plotted against the cons (higher computation time). Then the perfect balance between computation times and result improvement can also be found.

Table 9: Settings sensitivity analysis

Test Nr.	Time Step Size (min)	Branch and Bound	Max. Nr. of Transfers	Max. Access Wait Time (min)	Nr. of Skims
1	1	Strict	2	15	>0
2	2	Middle	3	30	>5
3	5	Loose	4	60	>11
4	10	Loose Extra	5	120	-
5	15	-	-	-	-
6	30	-	-	-	-

4 RESULTS

In this chapter all results are given. Results are given per type of analysis and all results are analysed and discussed.

4.1 SKIM COMPARISON

In this part, the skim results from the National Rail Model are used. Skim results are gathered using both methods. The results from the National Rail Model represent a real world situation, these are more valuable than the results from the test network. Results from the test network can be found in appendix C (C. Test network results). The settings of the skim generation can be found in appendix B (B. Settings). In appendix F (F. Amount of Connected skims) the amount of skims for the used SB dataset can be found.

4.1.1 In-Vehicle Travel Time

Results of the in-vehicle travel time comparison can be found in this section.

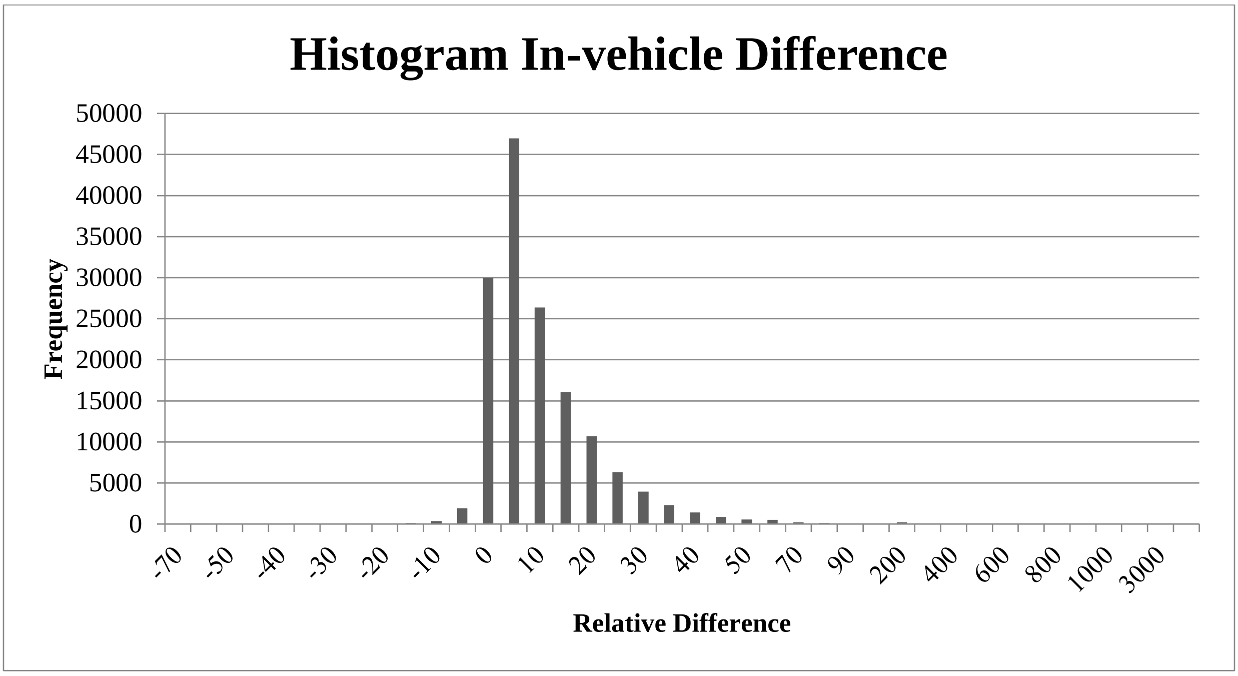

Figure 9: Histogram In-Vehicle Difference

The graph above (Figure 9), shows the relative difference for in-vehicle travel times. As can be seen from the graph, frequencies are a lot higher at the positive side. The median difference is 4,2%. It can be concluded that in vehicle travel times of the SB assignment are higher on average. Less optimal routes can become the best option when demand is equally spread over the entire hour, this can cause the higher in-vehicle travel time. For example: the SB method makes it possible that travellers arrive only minutes after the most optimal route has departed. These travellers are much less likely to make use of the most optimal route, because of the longer waiting time. In a FB assignment the preferred time of departure is not taken into account, therefore it is much more likely the optimal route is used by this method.

The accuracy of the difference can be seen in the table below (Table 10). The table shows the percentage of results that are within a certain difference interval from 0%. For example: 51% of all SB in-vehicle travel times deviate ±5% from the FB in-vehicle travel times. From this data, it can be seen that there is a significant difference between both in-vehicle travel time skims. However, most results only have a small difference.

Table 10: Accuracy of Results

Interval	Percentage of results
±5%	51%
±10%	71%
±15%	82%
±30%	96%

From the scatter plot below (Figure 10), the demand that belongs to a certain difference is shown. As can be seen, most high demand results are located on the line of zero difference. It can be concluded from the graph, that most high-demand relations only have a very small deviation. Most large deviations can be found in less used OD relations. The same scatter plot but with a travel time difference expressed in percentage can be found in appendix H (H. Relative Scatter Plot In-Vehicle Comparison).

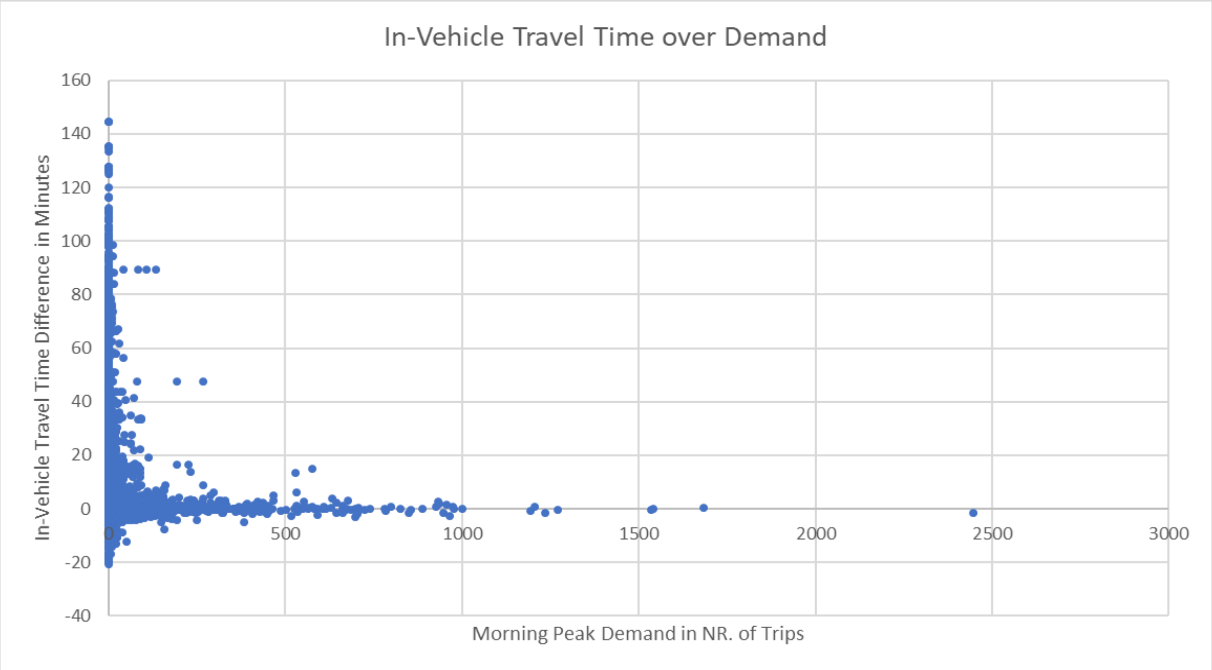

Figure 10: In-Vehicle Travel Time Difference over Demand

4.1.2 Total travel Time

The first comparison that has been done is the difference of total travel time. Results are gathered as described in the methodology. In the histogram below (Figure 11) the total travel time difference can be seen. From the histogram it becomes very clear that it has a slight deviation to the right. From the deviation it can be concluded that the FB algorithm gives slightly lower travel times than the SB algorithm. The median value is 2,4 minutes, which confirms this conclusion. These results are caused by the higher in-vehicle travel times. The table below (Table 11) shows the percentage of results that are within a certain difference interval from 0%. Data in the table shows the same pattern. As can be seen, there is a higher percentage of results above 0%.

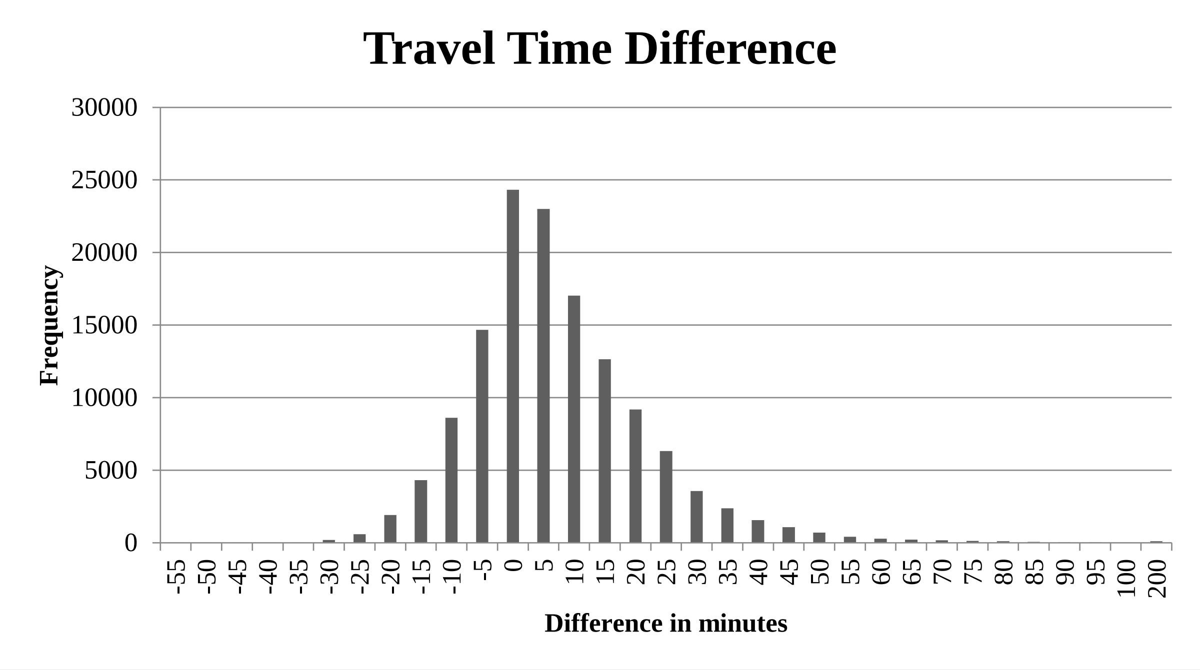

Figure 11: Histogram Total Travel Time Difference

Table 11: Relative Difference of Travel Times

Interval	Percentage of results
+30%	58%
+15%	49%
+10%	39%
+5%	22%
-5%	21%
-10%	34%
-15%	39%
-30%	41%

4.1.3 Waiting time

Subsequently, the results of the waiting time comparison are given. First, the total waiting time difference histogram is given. Total waiting time consists of two elements: access and transfer waiting time, both elements are also analysed. The histograms of access and transfer waiting times are given in appendix D (D. Waiting time results).

As can be seen from Figure 12, the frequencies are slightly higher at the left side of the graph. This means that waiting times are lower for the SB assignment. The median difference is -2,1 minutes. In the table below (Table 12), percentage of results that are within a certain difference interval from 0% can be seen. Percentages in the table also show lower travel times for the SB assignment. To find out where the differences come from the component skims are also analysed.

Since the access waiting time is a part of the total waiting time, access waiting times can possibly explain the results from the total travel time. The median of the difference in access waiting time is 0,5 minutes. From the median, it be seen that the SB access wait time is slightly higher. This might be caused by the perfect distribution of a FB assignment. The SB assignments assigns travellers every time step, therefore the size of the time steps influence the access waiting time. With a FB assignment, travellers receive an average waiting time based on an equal distribution over the time period. Overall, the waiting time is lower for a SB assignment, therefore it cannot be caused by the access waiting time. In appendix D.1 (D.1 Access waiting time) a full analysis of the access waiting time can be found.

The transfer waiting time is also part of the total waiting time. It became clear that the access wait time was not responsible for the lower total waiting times for a SB assignment, therefore the transfer waiting time must be responsible for this result. The median of -3 minutes, clearly shows a lower waiting time for transfers. In appendix D.2 (D.2 Transfer waiting time) a full analysis of the transfer waiting time can be found. It becomes clear that the transfer waiting time is the reason for the lower total waiting times for a SB assignment. This is caused by the more detailed calculation of the transfer waiting time by the Sb method. Most transfers are the Dutch rail network are synchronised, which means that very short transfers are guaranteed. The FB assignment is not able to calculate these transfer times exactly, instead it is only able to give an average waiting time based on the frequency. With the SB assignment, the short transfer time can be modelled.

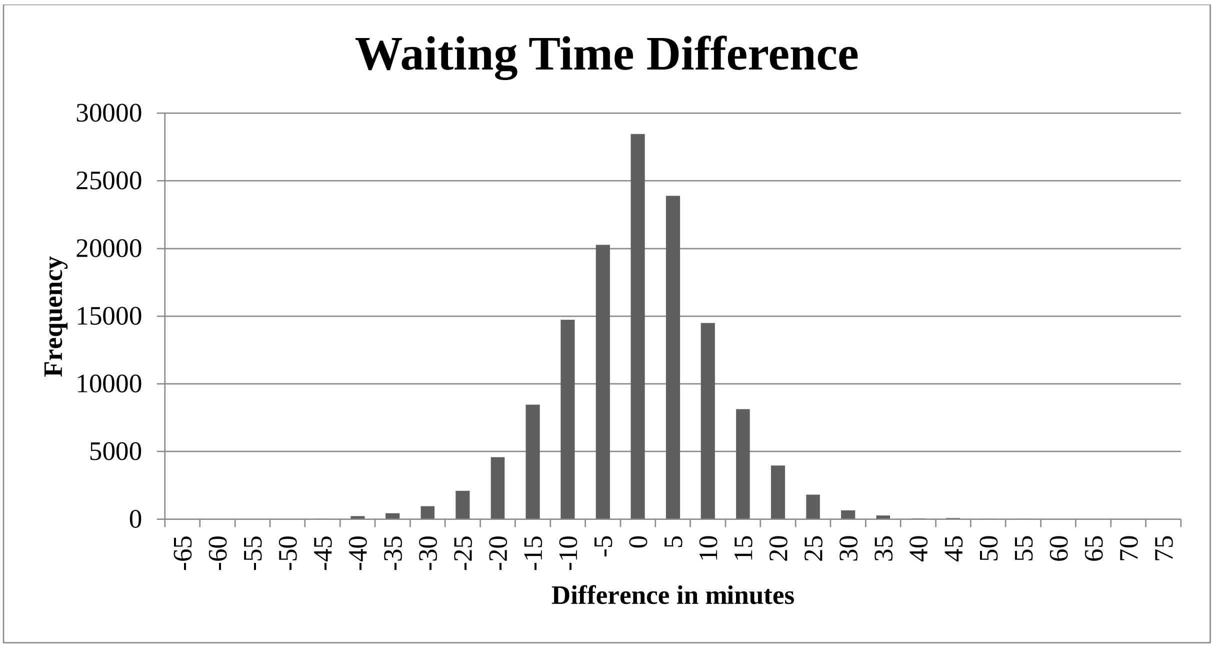

Figure 12: Histogram Waiting Time Difference

Table 12: Relative Difference of Waiting Times

Interval	Percentage of results
+30%	27%
+15%	17%
+10%	12%
+5%	6%
-5%	7%
-10%	14%
-15%	21%
-30%	42%

4.1.4 Penalties

To get more insight in the way penalties are assigned with both methods, the difference between penalties is also analysed. Differences are shown in the histogram below (Figure 13). The histogram clearly shows a deviation to the left. From the deviation, it can be concluded that there are less penalties given for a SB assignment. But, as can be seen, the difference is very small. Most relations get almost the same penalty: almost 90% of the relations have less than 5 minutes difference. The SB assignments has a slightly higher preference for the most direct route, concluding from these results.

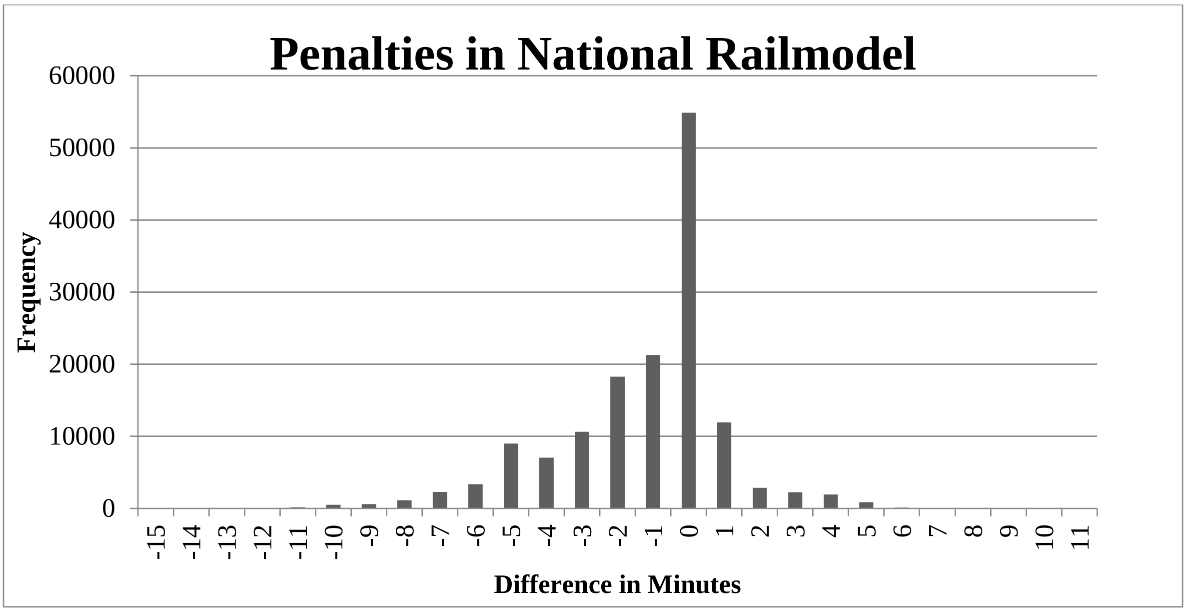

Figure 13: Difference in Penalties

4.1.5 Travel times in different scenarios

The median travel times in different situation is analysed to get more understanding in the way the skim result of both methods compare.

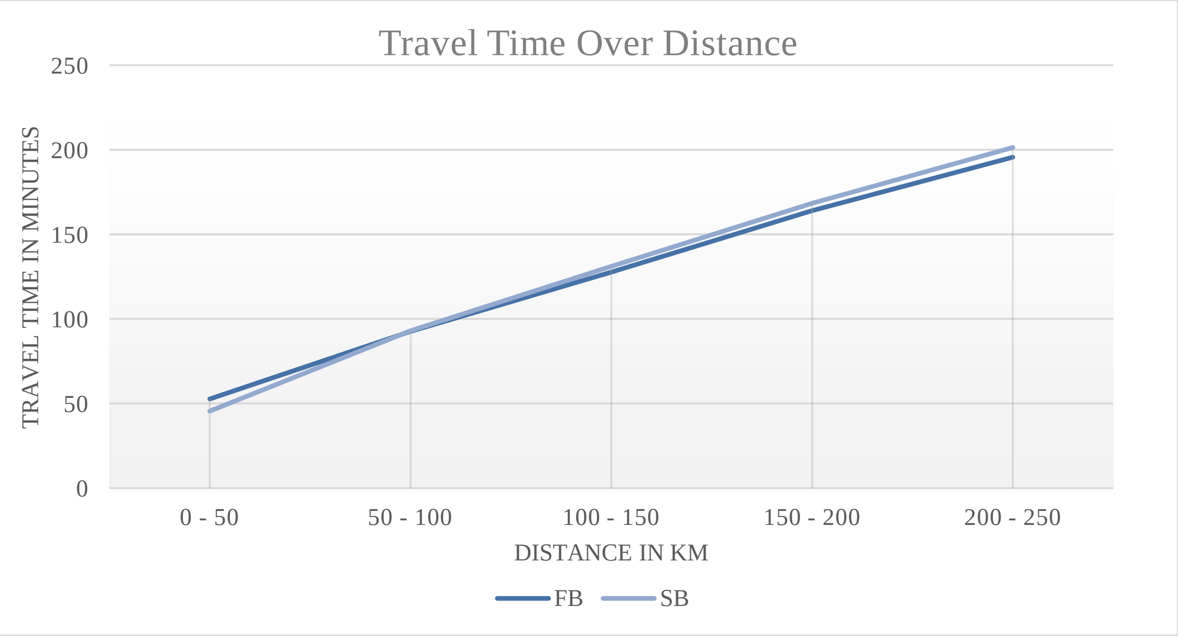

Figure 14: Travel Time over Distance Categories

From the graph above (Figure 14), it can be seen that the median value for both approaches over different distance categories stays almost the same. It can be clearly seen that travel times rise for larger distances. For long distances, the FB approach gives slightly lower travel times, but this difference is not significantly large. For short distances, the SB approach gives slightly lower results. Nevertheless, the overall trend is that travel times are the same in every distance category.

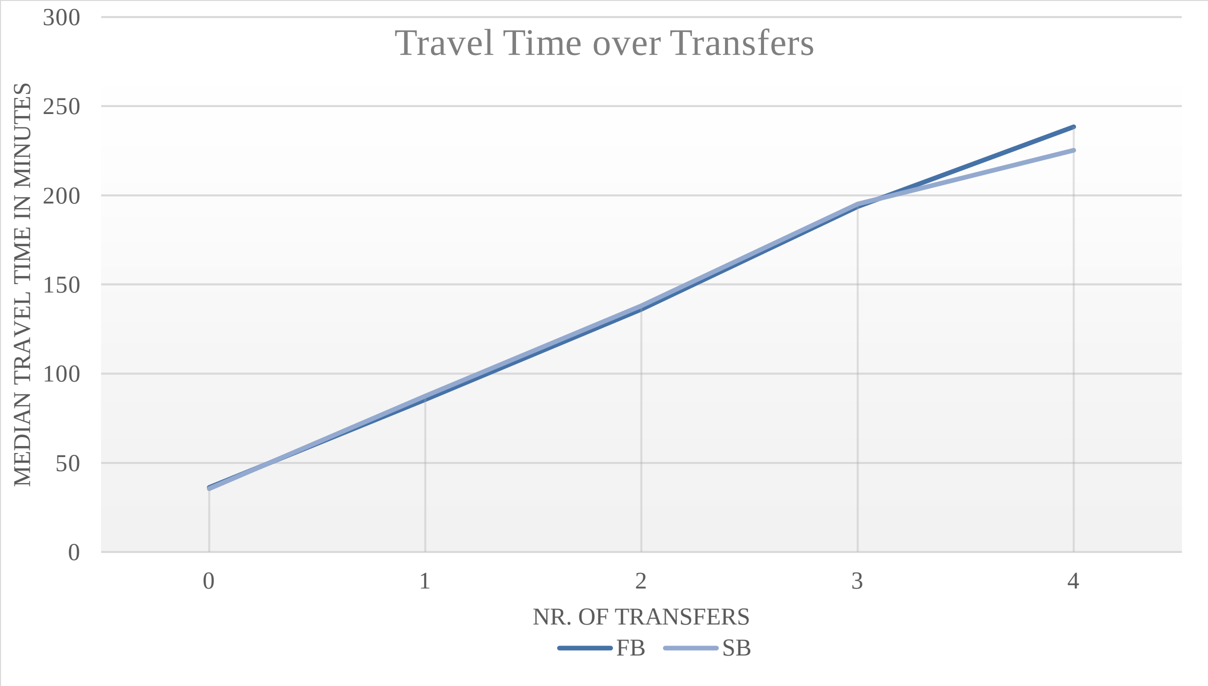

Figure 15: Travel Time over Nr. of Transfers

The graph above (Figure 15), shows that the travel times are almost equal for both methods until 3 transfers. At more than 3 transfers the SB travel time becomes smaller. This is caused by the more detailed calculation of transfer time as mentioned earlier. It is also possible that the divergent result is caused by the lack of relations that have more than 3 transfers. There are only 100 relations with this many transfers for both methods, this might give unreliable results for this category. Overall, the result is not what was expected. The expectation was that the SB assignment would give smaller travel times when transfers are present.

4.2 In-depth analysis

In this part, results from certain relation with specific characteristics are given. There are seven categories: high frequency, low frequency, transfer required, alternating, direct, short distance and long distance. For every category four OD-pairs are observed in both directions. In appendix G (G. in-Depth Description of an Example) an example of an OD relation is described in full detail.

Relations with high frequencies are defined as relations with four or more direct trains per hour. Relations with low frequencies are defined as relations with less than two direct trains per hour. The relations with transfers are defined as relations with no direct train connections. Alternating relations are defined as relations with at least one direct and one indirect connection per hour: if a transfer is needed to reach the destination, depends on the persons departure time. Direct relations are defined as relations where there is a direct connection available and where a route with transfers is much longer. Relations with short distances are defined as relations that are less than 30 km in length. Relations with long distances are defined as relations that are more than 200 km in length.

The average skim results for all used relations with that characteristic, are shown in the table below (Table 13). For each characteristic the average SB and FB travel times (including waiting times) are given in the table under “SB” and “FB”. Under “SB WT” and “FB WT” the access waiting times can be found. In the column “Real Time” the average of the fastest travel times between O and D according to the NS route planning app is given. The last columns contains the schedule and FB deviation to the “Real Time” respectively. This deviation is calculated by subtracting the access waiting times in the table from the travel times. The skim results per OD-pair can be seen in appendix I (I. In-Depth Analysis).

Table 13: In-Depth Analysis: Average Results

Characteristic	Real Time [min]	SB [min]	SB WT [min]	SB Deviation [min]	FB [min]	FB WT [min]	FB Deviation [min]
High Frequency	15	23	6	1	22	5	2
Low Frequency	43	64	22	0	63	19	2
Transfer	48	66	12	7	68	10	10
Alternating	138	166	25	3	164	18	8
Direct	28	41	12	2	40	9	3
Short Distance	16	29	12	1	29	11	2
Long Distance	247	268	20	2	257	14	-10

As can be seen, the relations with high frequencies have low deviations from the “real time”. The access waiting times are very small, this is expected, since trains depart very frequent. Overall, the deviation of the SB assignment is smaller than the FB deviation. Passenger proportions over sub-optimal routes might also the cause of the deviations.

The low frequency relations have large access waiting times, which can be explained by the infrequent departure of trains. The deviation of the SB assignment is very small for this characteristic and the FB assignment gives slightly higher deviations.

For relations with a required transfer, deviations of both methods are larger than in the first categories. This is caused by the proportion of travellers using sub-optimal routes. Still, the SB assignment gives a smaller deviation. This is the expected result. A more detailed calculation is most probably the cause of the smaller deviation for the SB assignment.

As can be seen from the table, for alternating relations the deviation of the FB assignment is much larger. Transfers on the route might cause this, because a more detailed calculation of transfer wait time can result in lower deviations. It can also be seen that the access waiting times are very long for the SB method. These long access waiting time suggest that the direct connection is mainly used. This also depends on the used parameters, in this case, parameter settings are the cause of the preferred direct routes. In appendix F (G. in-Depth Description of an Example) an alternating example is elaborated more.

From the table, it becomes clear that there is not much difference between the SB and FB assignment for direct relations. The difference in deviation is caused by proportion of passengers using sub-optimal routes. For short distance relations, it is the same situation. Overall, no remarkable situations exist in these categories.

The table clearly shows that the long distance relations have a large deviation for the FB results. Most of these differences are probably caused by the date differences of the data used. Since long distance relations are likely to have transfers, transfer waiting time calculation might have caused the smaller deviation from the SB method.

4.3 Sensitivity of parameters

The sensitivity analysis has been carried out for many parameters and for two KPIs. To show results more compact, two graphs are used to show the results. In the graphs below the results of the sensitivity analysis can be seen. The first graph (Figure 16), shows the effect on the median travel time and the second graph (Figure 17), shows the effect on the median travel time difference. The test numbers in these graphs correspond with the tests found in Table 9. In appendix E (E. graphs sensitivity analysis), all graphs for all parameters and all KPIs can be found separately.

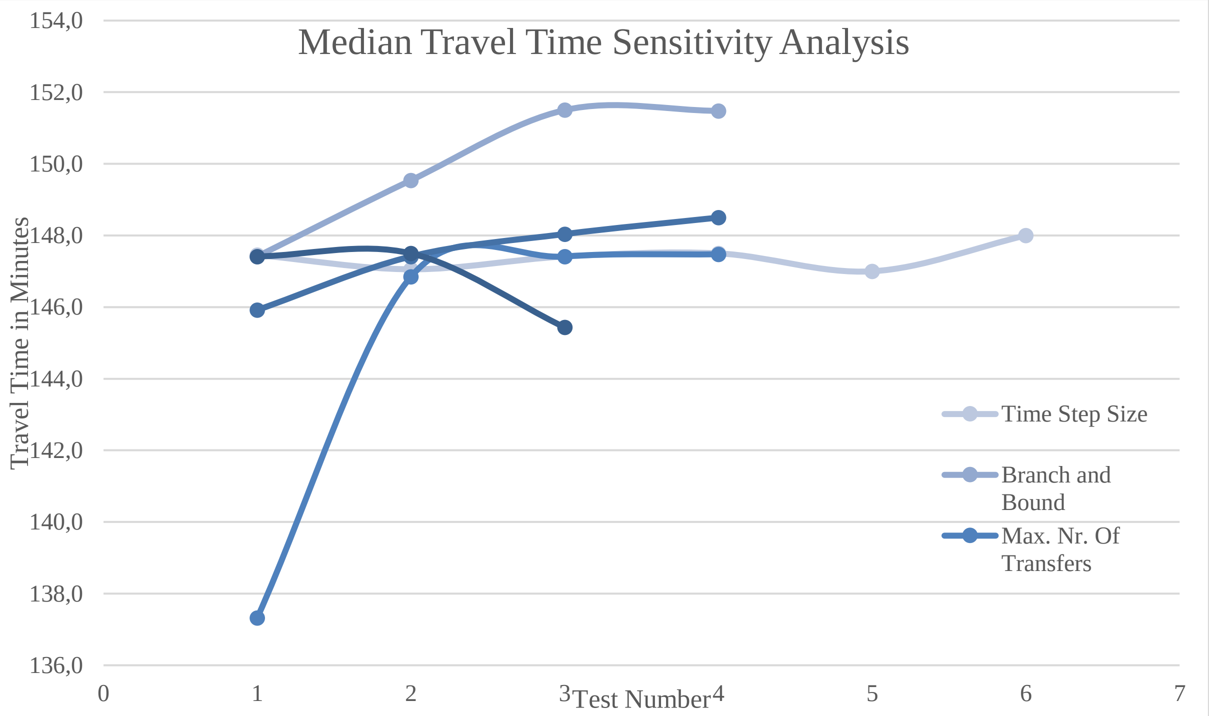

Figure 16: Median Travel Time Sensitivity Analysis

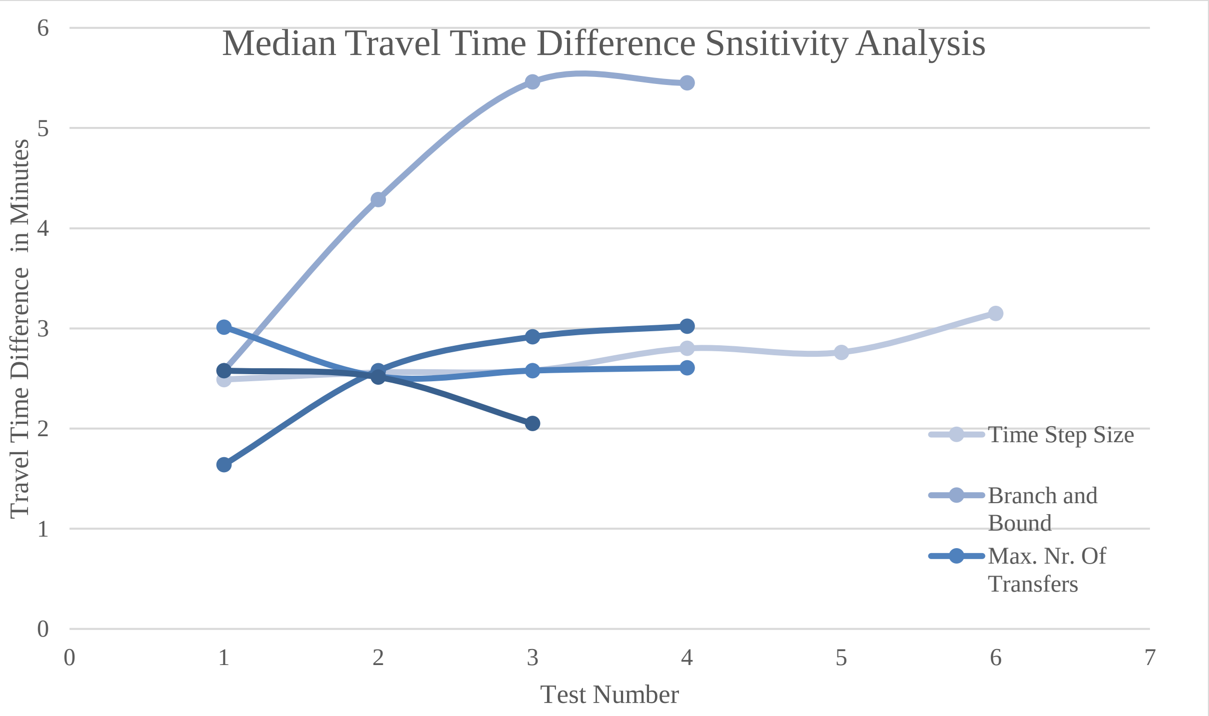

Figure 17: Median Travel Time Difference Sensitivity Analysis

4.3.1 Timestep settings

In the table below (Table 14), the run-time of every test can be seen. It becomes clear that the run-time is almost directly proportional to time step size. Run-time of an FB method on the same network takes 45 seconds (same settings as for skim comparison). It is very clear that almost all run-times are higher for the SB assignment. The results of the sensitivity analysis can be seen at the graphs above (Figure 16 and Figure 17).As can be seen from the graphs, the time step size has no large effects on the travel time. Only the 30 minutes time step size seems to have influence. The median stay almost the same for both graphs. This might be caused by the fact that it only has effect on individual runs and not on the total average or median of all runs. The 15 minutes time step size is selected as the most ideal setting, since it has no significant effect, but does have a very small run-time. The more detailed graphs that can be seen in appendix E.1 (E.1 Time step size), show the same results.

Table 14: Time Step Size Run-time

Test Nr.	Time step	Run-time
1	1 min	479 seconds
2	2 min	284 seconds
3	5 min	109 seconds
4	10 min	57 seconds
5	15 min	43 seconds
6	30 min	27 seconds

4.3.2 Branch and bound settings

In the table below (Table 15) the run-time per setting can be seen. The table clearly shows that the run-time increases drastically for the loose settings. The results of the sensitivity analysis can be seen in the graphs above (Figure 16 and Figure 17). From the graph, it can be clearly seen that the branch and bound settings have a significant effect on the travel time of the SB assignment. The line increased monotonously from strict to loose settings. The addition of an extra transfer in the "Loose extra" setting makes no difference. The branch and bound settings influence is also influenced by the logit parameter. In this case, the logit parameter allows for the usage of less optimal routes, which increases travel time. When using a higher logit parameter value, this effect would be smaller. It is assumed that the detail added with less strict settings, makes the travel time calculation more accurate. Considering this assumption, the best setting is: 'middle'. The 'middle' setting only gives a slight increase in run-time, but has a significant effect on the results. The more detailed graphs can be seen in appendix E.2 (E.2 branch and bound).

Table 15: Branch and Bound Run-time

Test Nr.	Setting	Run-time
1	Strict	105
2	Middle	161
3	Loose	424
4	Loose Extra	576

4.3.3 Maximum transfers

In the table below (Table 16), the run-time for every setting can be seen. From the table, it becomes clear that more than three interchanges do not influence the run-time significantly. This might be caused by the fact that there are very few OD relations with this many transfers. In the graphs above (Figure 16 and Figure 17), the results of the sensitivity analysis can be seen. From the results, it becomes clear that the travel time increases drastically from two to three transfers. After three or more transfers, the travel time does not change very much. The fact that the travel time increases very much from two to three, can be caused by the number of skims that are used in the travel time calculation. There are only nine skims per OD-pair on average, for two transfers. Routes with more than two transfers are neglected, therefore a lot of OD connections are not possible, which causes the low amount of skims. The difference with the FB travel time shows the same result. The best setting is considered to be maximum 5 transfers. This settings allows for a more accurate assignment, but does not have a large influence on run-time or skim results. More detailed graphs and number of skims can be seen in appendix E.3 (E.3 Maximum nr. of transfers).

Table 16: Maximum Transfers Run-time

Test Nr.	Maximum Interchanges	Run-time
1	2	68
2	3	94
3	4	104
4	5	105

4.3.4 Maximum Access waiting time

In the table below (Table 17), the run-time per setting can be seen. As can be seen the run-time does not change after 30 minutes of access waiting time. In the graphs above (Figure 16 and Figure 17), the results of the sensitivity analysis are shown. From the graphs, it becomes clear that access wait time has a large effect from 15 to 60 minutes, after that the effect flattens. The steep line between 15 and 30 minutes can be the cause of the lack of skims used in the calculation of travel time. There are only nine skims on average with 15 minutes of access wait time. The low number of skims make the results unreliable. The best value for the maximum access waiting time, concluding from these results is: 120 minutes access waiting time. This setting includes the most skim results and also has no significant effect on the run-time. More detailed graphs and number of skims can be found in appendix E.4 (E.4 maximum access waiting time).

Table 17: Maximum Access Wait Time Run-time

Test Nr.	Maximum Access Waiting Time	Run-time
1	15	99
2	30	109
3	60	104
4	120	102

4.3.5 Minimum number of skim values

In the graph below, the used tests are shown (Table 18). The results of the sensitivity analysis can be seen in the graphs above (Figure 16 and Figure 17). It becomes clear that there is only an effect visible on the travel time, when there are more than 11 skims needed per OD-pair. This effect is caused by the lack of useful OD-pairs for this setting. OD-pairs with less than 12 useful skim results are ignored in the calculation for this setting. Since there are a lot of skims with less than 12 useful skim results, the total travel time is influenced a lot. It can be concluded from these results that more than 11 skims is the best setting. This setting only included OD-pairs, from which a route can be constructed for every time step, these are considered to be the most reliable. With this setting, the travel times are also decreased. More detailed graphs can be seen in appendix E.5 (E.5 minimum nr. of skim values).

Table 18: Tests for min. nr. of skims

Test Nr.	Nr. of Skims
1	>0
2	>5
3	>11

5 Conclusions

To come to a final conclusion the sub-questions and main research question of section 1.4 have to be answered. First the sub-questions are answered and from the question the main question is answered. Answerers to the questions are based on the results with consideration of the theory.

5.1 Sub-Questions

From the analysis of the verification results the following question is answered: *What are the main practical differences between both methods?* The following conclusions can be drawn from the theory, the application on the case network and the results.

Input for a SB assignment always needs to take the temporal aspect into account. However, apart from determined schedules, most input data is almost the same as for a SB assignment. More significant differences can be found in the parameter settings for both methods. Many more parameters have to be defined to perform an SB assignment. All these settings can have large effects on the outcomes, as can be concluded from the sensitivity analysis. Concerning the run-times of both methods, there is also a large difference. As can be seen from the sensitivity analysis results, most SB assignments have much longer run-times than a FB assignment, depending on the settings. From the skim gathering it also became clear that result are also much different for both methods. SB skim results are gathered per time step, whereas the FB assignments creates one single skim for the entire simulated time step.

From the analysis of the skim comparison results the following question is answered: *How do the skims of the SB algorithm compare to results from the FB algorithm?* The following conclusions can be drawn from the results.

From the results of the quantitative and in-depth comparison it becomes clear that the in-vehicle travel times are much larger for schedule based assignments. Also, the total travel time, calculated by the SB method, is significantly higher than the FB travel times. Both higher outcomes, are the result of a sub-optimal route choice, caused by the demand spread over the time steps and the limitations of the maximum access wait time. SB waiting times are lower on average and this is caused by the transfer waiting time. The results also show that an almost equal amount of penalties is given for both methods, with slightly more penalties for the FB method. From the analysis of different categories, it becomes clear that no significant differences can be found when looking at distance or transfer categories. Deviations from the ‘real-world’ data are larger for the FB method. It can also be seen that the categories observed show deviations conform the theories. Overall, the methods seems to behave as expected in some cases and the deviations from ‘real-world data has become smaller.

From the analysis of the sensitivity analysis results the following question is answered: *What is the influence of different parameters of the SB algorithm?* The following conclusions can be drawn from the results.

The sensitivity analysis shows that time steps do not influence results very much, but do influence the run-time. Branch and bound settings have large influence on results and on run-time. An extra transfer in the branch and bound settings has no influence. Maximum number of transfers only influences run-time, if there are still optimal options with that many transfers. Low maximum number of transfers mainly influences number of skims, which causes a change in outcome. Low maximum access waiting time also mainly influences number of skims. Run-times do not grow with the maximum access waiting time. Number of skims can have large influences, high limits cause less skims to be considered, which causes a change in outcome. Overall, the best settings to use concluding from the results is: 15 minutes time steps, middle settings for branch and bound, maximum of five transfers, 120 minutes access waiting time, minimal 12 skims per OD-pair.

5.2 MAIN RESEARCH QUESTION

The final conclusion gives answer to the main research question: *What are the main differences between the schedule based and frequency based methods in a practical application and what influences these differences*?

There are many differences between the SB an FB methods. Many differences can be found in the application of the methods. As literature confirms, SB assignments are more time consuming, not only in run-time, but also in determining the right parameters for an assignment. SB assignments are most influenced by the branch and bound and the maximum access waiting time settings. These parameters have to be defined correctly, in order to perform accurate assignments. Skim results from both methods also have some significant differences. Other route choices, caused by the temporal aspects of the SB method, are the reason for larger overall travel times. Transfer time calculation seems to be done more accurately by SB methods. Overall, the SB method also gives results closer to the 'real world' travel times. It can be said that for some scenarios, especially scenarios with transfers, the SB method is a better way of assigning travellers on routes. However, parameter settings need to be defined very accurately in order for the SB method to give realistic outcomes.

6 Discussion and Recommendation

In this chapter the total research is discussed. First, the validity and the limitations of the study are described. Subsequently, an interpretation of the conclusions and results is given. A recommendation is given in the end.

6.1 Limitations

The research was conducted based on several assumptions. Some of these assumptions were done to make a comparison between both methods possible. Settings for both methods needed to be comparable, this made it harder to optimize settings for both methods. When applying a schedule based assignment, it is possible to use demand fluctuation. Demand fluctuation is one of the large benefits of the SB methods and would make a large difference, when implemented. This setting was not implemented in this study to make a comparison possible. The frequency based method is able to compute more realistic skims when bounding parameters are defined more strictly. These parameters make it possible to limit waiting times, which solves one of the shortcomings of the FB method. These limits were set very high to create a more honest comparison. This means that, in reality, both assignments are able to give more realistic results.

The lack of demand fluctuation in the study creates another shortcoming. For both assignments done in this study, demands were equal for every time step. This can result in unrealistic situations: travellers are able to arrive at the origin station, just after the most optimal solution departs. This results in the use of sub-optimal routes. In reality these situations are very rare. Some of the unexpected results can be explained by these situations.

There are some limitations to the data used in the study. The National Rail Model dates from 2013. This means that the transit lines, stations and timetable of 2013 is used. The real-world data that is used from the NS application is data from 2019. Differences between the data of the NS and the assignments can therefore be caused by the date difference.

The data from the NS application is only based of the most optimal route between O and D. Both the SB as the FB assignments also consider less optimal routes, therefore the modelled travel times of both methods will always be higher than the travel times gathered from the application. Data from the NS application is used as validation, however this cannot be considered as ground-truth data. As already mentioned, the NS data only considers the most optimal route, which is not what happens in reality. The NS data also lacks in access waiting times, which are an important factor in the line choice.

Since the algorithms are used inside the OmniTRANS software this can also cause some limitations. The OmniTRANS software is a so-called black-box. Input is entered and via the black-box some output is given. This unknown area might make it harder to explain results. Since knowledge is available, the black-box has partly been overcome.

A major limitation of this study was the malfunction of the SB algorithm. During the research several issues with the SB algorithm became clear. These issues are all described in appendix A (A. practical problems during research). Major changes to the algorithm were made during the research. This means that the algorithm used, with the recent changes, has not been validated with ground truth data.

6.2 Interpretation of results

Based on the limitations of the study the main conclusions are discussed. Some results and conclusions need to be interpreted differently.

It becomes clear from the results that the SB assignment gives smaller deviations from the NS data. From this result, it can be concluded that the SB assignment is more realistic. However, the NS data cannot be considered as ground truth data, which is already mentioned above. In addition, there is a data difference between the two data-sets. Therefore it is possible that the results of this comparison are not reliable. In a situation with data of equal date, which is ground-truth, the results could be different.

From the sensitivity analysis, the best settings for a SB assignments can be derived. These settings are as already mentioned: 15 minutes time steps, middle settings for branch and bound, maximum of five transfers, 60 minutes access waiting time, minimal 12 skims per OD-pair. These settings came out to be the most advantageous, considering influence and run-time. However, some of these settings are not useful in practice. The 15 minute time step setting gave a short run-time and did not give much different results from the other settings. However, time steps that are this large create a very low detail level. The benefits of the SB assignment are nullified for these settings, since the temporal aspects become very small with these large time steps.

6.3 Recommendation

To perform accurate SB assignments parameters have to be defined very carefully. Limitations of the SB assignment can be overcome by setting the parameters to the right values. Especially from a micro perspective, because the exact routes between certain OD-pairs need to be logical for these observations. For every scenario, the settings need to be critically observed and changed accordingly.

It is recommended to use schedule based assignments in situation were a lot of data is already available. It is not recommended to use these SB assignments for future planning purposes or quick scans of situations. When an in-depth analysis of a situation needs to be modelled a SB method is recommendable, especially in situations where transfers are required.

It is also recommended that the current SB algorithm is updated and validated. It is not known to what extend the current SB algorithm is reliable. The best way to validate the algorithm is to use a case study, in which amounts of passengers per transit line are known. Passenger data can then be considered as ground-truth data, which can be used for a validation of the algorithm. In this way, the use of the SB assignment is facilitated.

Some improvements to the current approaches can be found in the field of information providing systems. Overall the FB and SB methods described are based on standard behavioural assumptions of passengers route choice. Recently, new approaches emerged, which takes passengers adaptation and learning mechanisms in a dynamically varying system into account.
It is possible for ITS and APTS to provide to provide passengers with real-time information about the condition of the network. This information can be about: lines, schedules, departure times, arrival times, transfers or occupancy. These systems can provide this information via several media platforms and can do this both pre-trip or en-route.

These systems provide many benefits. They are able to provide less uncertainty in waiting, more goodwill for PT, more willingness-to-pay and less waiting times. Information provided by these systems could also impact departure time and route choice, this would affect the assignment over the network. The benefits of these systems are documented in several studies. All these benefits make it very attractive for transit companies to create these systems.
Traditional ways of PT planning have large limitations, when it comes to taking the effects of real-time information into account. Both FB and Sb methods used in this study are not sensitive to passengers reaction to information. More understanding in how passengers react to this information is needed to better ways of assigning passengers. (Liu, Bunker, & Ferreira, 2010)

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APPENDICES

A. PRACTICAL PROBLEMS DURING RESEARCH

A.1 Problems with test network

After the first SB assignments on the test network it became clear that there were some problems present. Skim results were very unrealistic. There were high travel times for very short routes and penalties were added at places were this was not necessary. A lot of trips were also not assigned to the network. These problems were all solved by the measures described below.

There was an error when not aggregating loads "TmpFile: couldn't create temp file X". It is caused by having too many open files, every single type of component and disaggregate skim possible in the script for 5 minute intervals is saved. That adds up to a lot of skim files that have to be opened. Smaller time slice (15 minutes) or 4, 5 minute time slices will solve the problems with the strange skim results.

```
# Fake dynamic OD demand. First 30min gets 15% of demand, etc.
if t==1
  #transit.scheduleDepartureFractions  = [0.05,  0.10, 0.10, 0.25, 0.20, 0.15, 0.10, 0.05]
  transit.scheduleDepartureFractions  = [1.0]
  #transit.scheduleDurations         = [15,    15,   15,   15,   15,   15,   15,   15]
  transit.scheduleDurations          = [20]
end

# Build a multi-path every scheduleTimeSteps minutes and spread the demand equally.
transit.scheduleTimeSteps = [5]
```

The other problem with the trips that were not allocated was solved by changing a parameter. These problems were caused by long access waiting times, these times were longer than the default limit of 20 minutes. This limit had to be increased to solve the problem. This setting can also be changed for the maximum transfer time.

```
transit.scheduleMaxAccessWaitTime = 40
```

A.2 Problems in National Rail Model

There was a bug with aggregation of loads. If you have aggregation enabled it seems to have a bug in the weighted summation when including 99999 leading to a 10033.75 or similar value for that cell.

There were some issues with the moved trips. Trips seem to have been moved to certain time slices in a random way. For the OD-pairs: 55 – 160 and 83 – 278 strips were moved to a subsequent time slice, but this was not necessary considering the maximum access waiting time. A very high access waiting time of 120 minutes was used to try and solve the problem, but it did not work.

Some unexpected skim results also caused issues. Between some OD-pairs (e.g. 162 – 67) skim values for travel time and penalties are not what is expected. Some travel times were shorter than the shortest possible in-vehicle travel time between these centroids. Some other OD-pairs have much longer travel times than would be expected. Most of the time these OD-pairs also have penalties, which suggest transfers. These transfers are very often not necessary on these routes. So these penalty skim values are also unexpected.

There were also some issues with not-allocated trips. On certain OD-pairs trips are not assigned at al. This happens with some OD-pairs that have a normal route between each other. An example of this problem is 64 – 184.

The issues were fixed by some changes in the algorithm. The change was that domination (bounding) criteria were being calculated based on the wait/penalty of the final leg in the connection chain. This effectively meant that paths were being removed from the choice set semi-randomly. Another fix was an issue with component skims (Access/Egress/Transfer/In-Vehicle) as well as a bug relating to stop types.

After this fix there were still some problems present in the network. The issue existed within alternating relations. An example is between centroids 22 and 230 (Groningen and Schiphol Airport) A direct train between these two leaves once every hour from Groningen. There is also a connection that requires passengers to transfer at Zwolle (70) to go to Schiphol which also leaves once every hour from Groningen. This transfer is cross-platform and only takes 2 minutes. Therefore the indirect route takes exactly the same time as the direct route. It is expected that travellers between 22 and 230 will almost only used these 2 routes and the direct route will be preferred.

However, the assignment results show something else. The results show that the direct connection is mainly used, which would be expected, but the route with a short transfer at Zwolle is not used at all. Instead of using that route, travellers transfer on strange places which lead to very long transfer waiting times. These routes can be seen from an animation in the first variant in the project.

The routes seem to make no sense, but after analysing the skims it became clear that these routes have a lower generalized cost than the route with the short transfer in Zwolle. This means that according to the algorithm this route is cheaper so travellers will make use of these routes.

The algorithm seemed to work correctly. However, it is quite tricky to understand why it is making the decisions that it is. The example OD-pair .(22 – 230) will be worked out.

Firstly if someone leaves at or before 7:46, catching the direct route (1682) to Schiphol is the best method and 100% of the demand does this. 60 minutes broken into 5 minute blocks gives us 12 time periods, 10 of which are < 7:46 (00,05,10,15,20,25,30,35,40,45) and 2 of which cannot take this service (7:50 and 7:55). Looking at the outputs, it can be seen that 83.3% of the demand does exactly this (10/12 = 83.3%).

So that leaves us with people leaving at 7:50 and 7:55.

There are two main lines to Schiphol from this corridor, the 1682 and the 1685. The 1682 is the direct line from Groningen and the 1685 is the coordinated service that was mentioned can be caught with a 2 minute interchange at Zwolle. However, the 1685 can also be caught quite easily from Meppel. In the image below (Figure 18) the two lines can be seen in red.

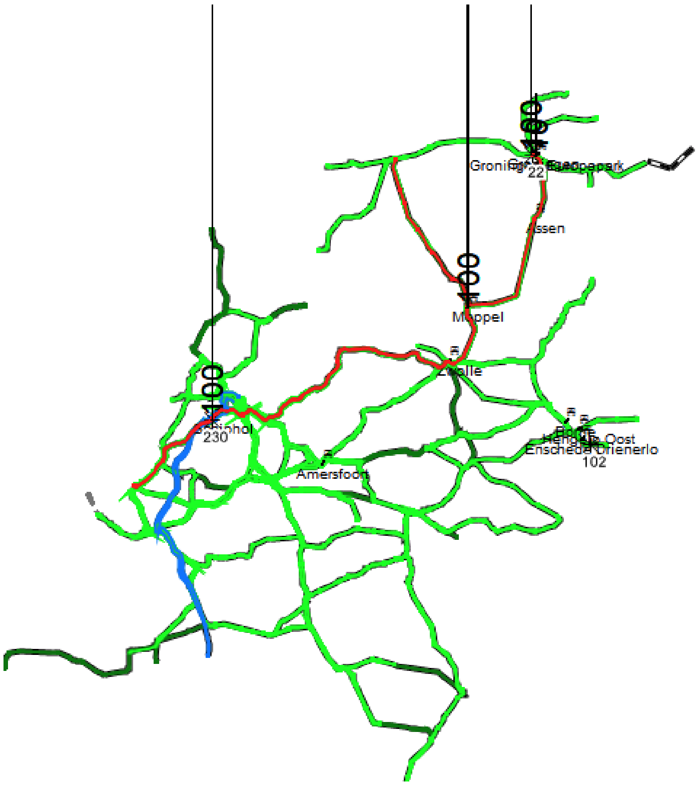

Figure 18: Groningen - Schiphol: Transfer at Meppel

For people leaving at 7:50, they can catch a train (route 2010) directly to Meppel and then from there to Schiphol. 90% of people leaving at 7:50 do this. However, It can also be sees that approximately 10% of them, first catch an east bound service for 1 stop and then interchange at Groningen Europapark, onto the 2010. They then behave exactly like the other 90% of people. This seems counter intuitive, but is because the algorithm isn't capable of seeing the degree of correlation between these two options and from a GC point of view, they aren't that dissimilar (5 minutes of interchange penalty on a 50 minute journey).

For people leaving at 7:55, they can't get to Meppel/Zwolle in time to make that interchange, so they need another option. The next best option is to take the 1682 direct route, but that (8:46=51 minute wait) would exceed the 30 minute max wait time that is used here, however, if they wait for 20 minutes and catch a local train south to Assen, they can then spend 30 minutes waiting for the 1682 there (which just sneaks under the 30 minute interchange cut off). So essentially, the choice is break the 51 minute wait time into 21 minutes (at Groningen) and 30 minutes (at Assen) or not be able to get to Schiphol at all. This can be seen in Figure 19. This is an example of a hard cut off leading to nonsensical outcomes when viewed at the micro level. However, in this case if it was runned with normal assumptions about demand temporal spreading – it is not expected that a large number of people to turn up to Groningen heading for Schiphol, two minutes after the direct service leaves - and if demand that is so un-synchronized from the supply is not used - then there is the facility of the algorithm to defer that demand to a time slice that is more conducive to travel.

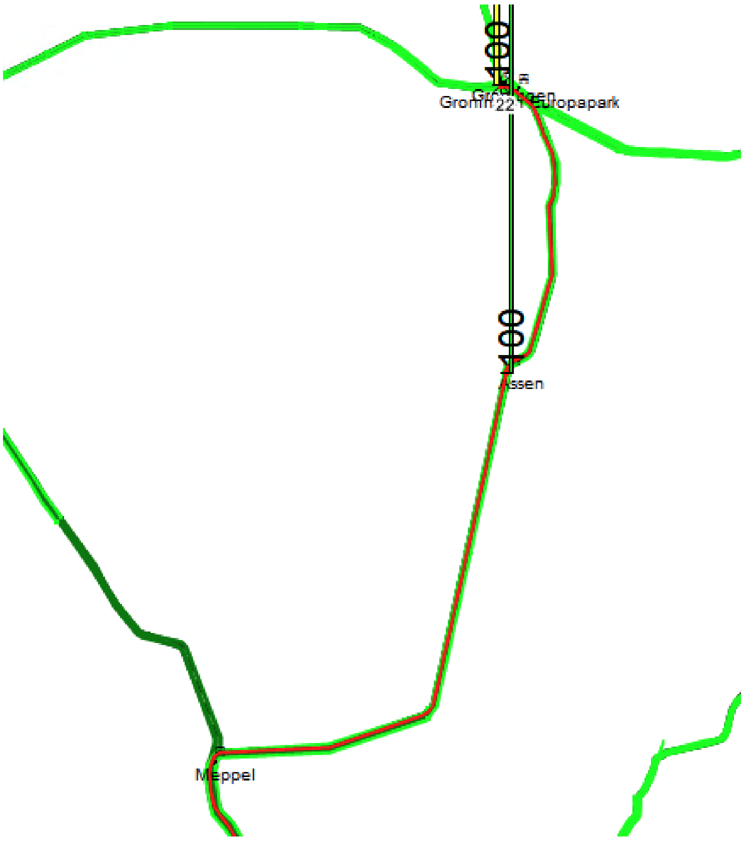

Figure 19: Groningen - Schiphol: Transfer at Assen

So in summary, there are some limitations of the algorithm, but it is expected that, in general use, they can be worked around. For example setting 30 minute wait + 30 min interchanges allows a lot of latitude in assigning a time slice - dropping these down would allow the algorithm to disconnect the OD's and move the demand forward to a time slice that doesn't have such a large waiting time component.

B. Settings

In this appendix the all settings used in the assignments are shown.

B.1 Settings of test network application

Table 19: SB Settings of application in Test Network

Settings for SB algorithm	Value
Probability parameters	0,02
Logit parameters	0,6
Demand matrix period	07:00 till 09:00 (morning rush hour)
Assigned time period	07:00 till 08:00
Time step	5 minutes
Maximum interchanges	4
Maximum access waiting time	60 minutes
Maximum interchange waiting time	30 minutes
Cool down period	360 minutes
Minimum amount of connected skims per OD	6 skims

Table 20: FB Settings of application in Test Network

Settings for FB algorithm	Value
Probability parameters	0,01 and 0,02
Logit parameters	0,6
Demand matrix period	07:00 till 09:00 (morning rush hour)
Assigned time period	07:00 till 09:00
Maximum interchanges	5
Maximum access waiting time	60 minutes
Maximum transfer waiting time	60 minutes

B.2 Settings for main skim comparison

Table 21: SB settings for main skim comparison

Settings for SB algorithm	Value
Probability parameters	0,02
Logit parameters	0,6
Demand matrix period	07:00 till 09:00 (morning rush hour)
Assigned time period	07:00 till 08:00
Time step	5 minutes
Maximum interchanges	4
Maximum access waiting time	30 minutes
Maximum interchange waiting time	30 minutes
Cool down period	360 minutes
Minimum amount of connected skims per OD	6 skims

Table 22: FB settings for main skim comparison

Settings for FB algorithm	Value
Probability parameters	0,01 and 0,02
Logit parameters	0,6
Demand matrix period	07:00 till 09:00 (morning rush hour)
Assigned time period	07:00 till 09:00
Maximum interchanges	5
Maximum access waiting time	60 minutes

C. TEST NETWORK RESULTS

The test network was initially used to gain more insight in the application of the SB method. Both assignments were also applied on the test network and compared. Results of the comparison are shown here. In the test network the travel times are compared for normal situation and for different frequency situations. Settings of the skim generation can be found in appendix B.1 (B.1 Settings of test network application).

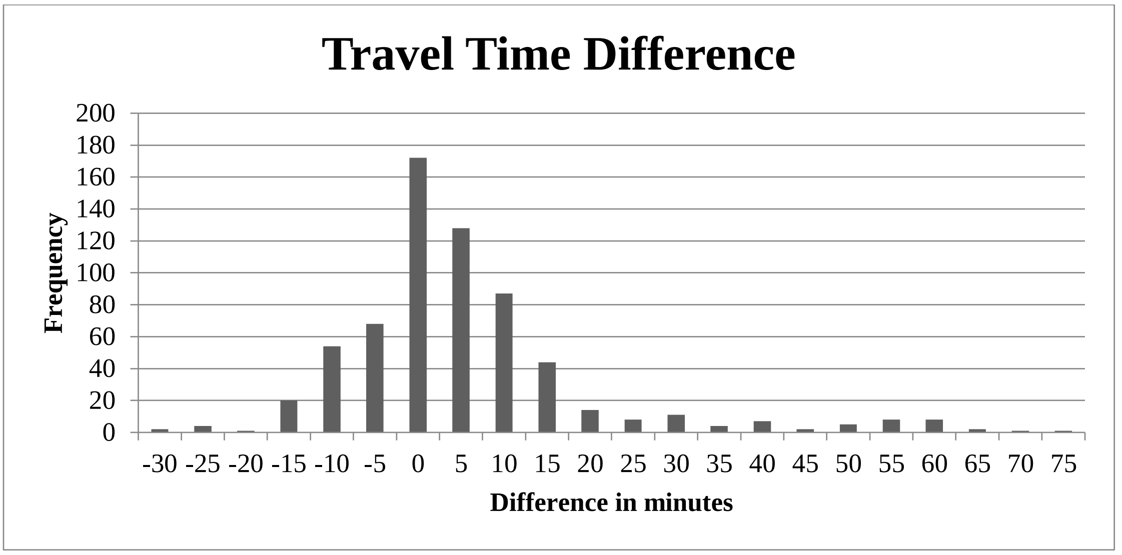

Figure 20: Travel time Difference in test network

From the graph above (Figure 20) it can be seen that the SB travel times are higher than the FB results. The median value is 0,2 minutes. In the test network transfers do not connect. This means that transfer waiting times can sometimes be high. High transfer times is the reason that the SB assignment gives higher travel times on average. FB transfer times are based on the frequency of the transit lines, which will result in lower transfer times when transfers connect poorly.

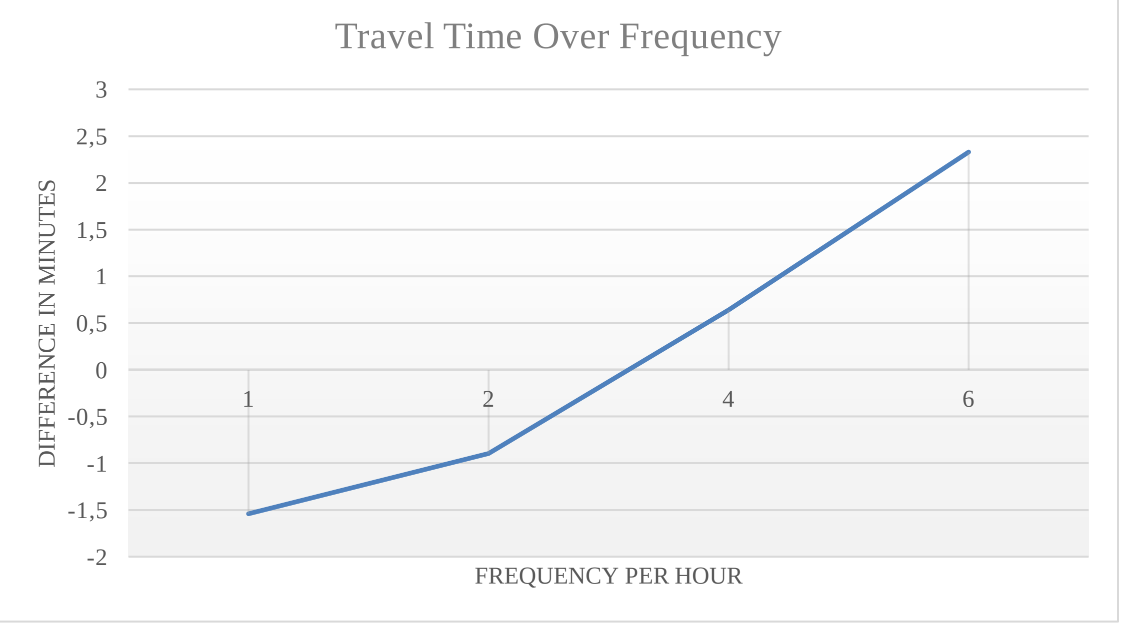

Figure 21: Travel Time in Test Network over Frequency

In the graph above (Figure 21) the effect of the frequency on the difference in travel times can be found. As can be seen with low frequencies the FB method gives higher results. This makes sense, because very low frequencies result in very high waiting times for FB assignments. High frequencies result in higher travel times for the SB assignment. Since high frequencies cause low waiting times with a FB assignment this is an expected result.

D. Waiting time results

In this part the results other elements of the total waiting time are given.

D.1 Access waiting time

As can be seen from the histogram below (Figure 22) the access waiting time difference deviates slightly to the right. It can be concluded that the access waiting time is larger for a SB approach. In the table below (Table 23) the relative difference over several intervals are given. The table shows the same result: there is an higher percentage above 0%. However, all differences are very small and as most results only have a small difference.

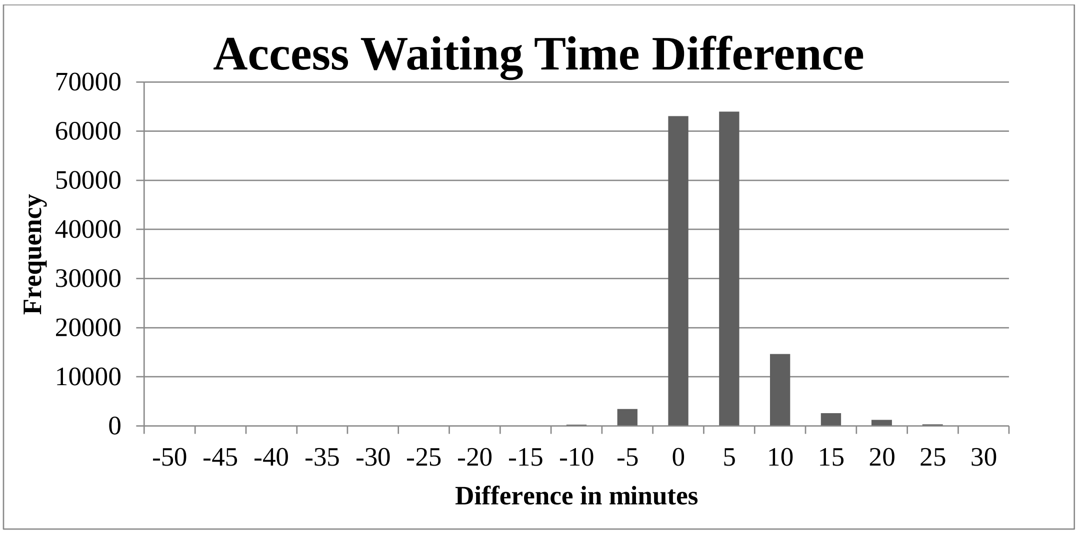

Figure 22: Histogram Access Waiting Time Difference

Table 23: Relative Difference of Access Waiting Times

Interval	Percentage of results
+30%	38%
+15%	24%
+10%	15%
+5%	9%
-5%	8%
-10%	18%
-15%	21%
-30%	31%

D.2 Transfer waiting time

It can be seen from the histogram (Figure 23) that the transfer waiting time is, as predicted, the cause for the lower total waiting times for the SB assignment. The same result can also be seen from the percentage of results in a certain interval (Table 24).

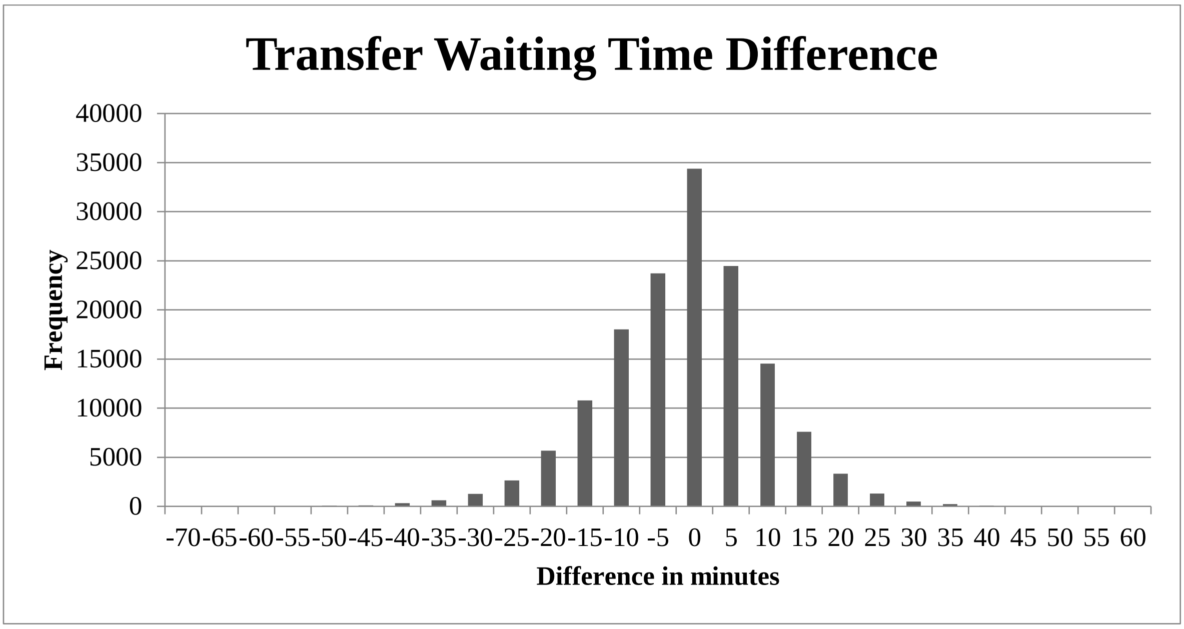

Figure 23: Histogram Transfer Waiting Time Difference

Table 24: Relative Difference of Transfer Waiting Times

Interval	Percentage of results
+30%	19%
+15%	11%
+10%	8%
+5%	4%
-5%	4%
-10%	9%
-15%	14%
-30%	29%

E. GRAPHS SENSITIVITY ANALYSIS

All detailed graphs of the sensitivity analysis can be found in the appendix.

E.1 Time step size

In the graphs (Figure 24 and Figure 25) below the results of the sensitivity analysis for time step size can be found.

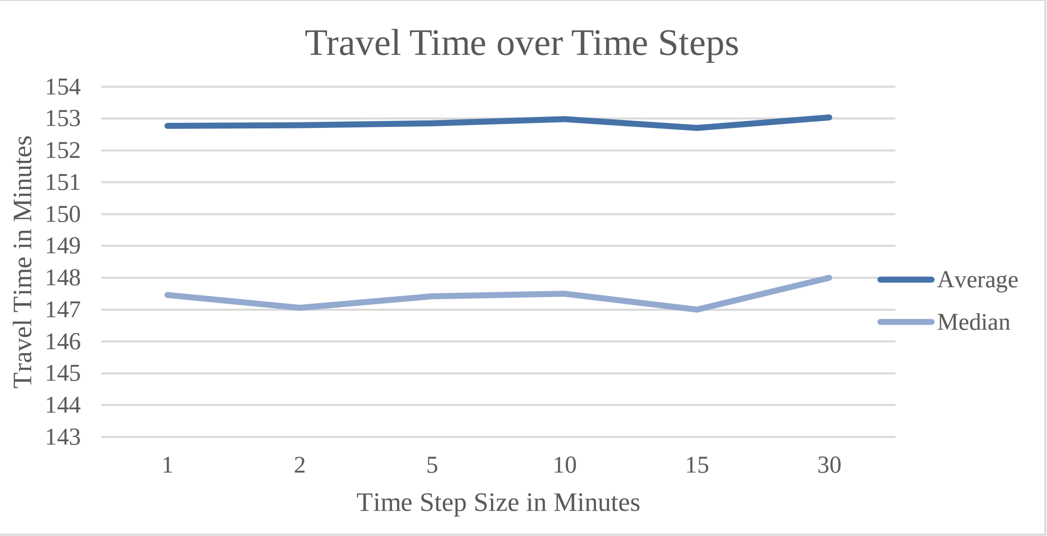

Figure 24: Travel Time over Time Steps

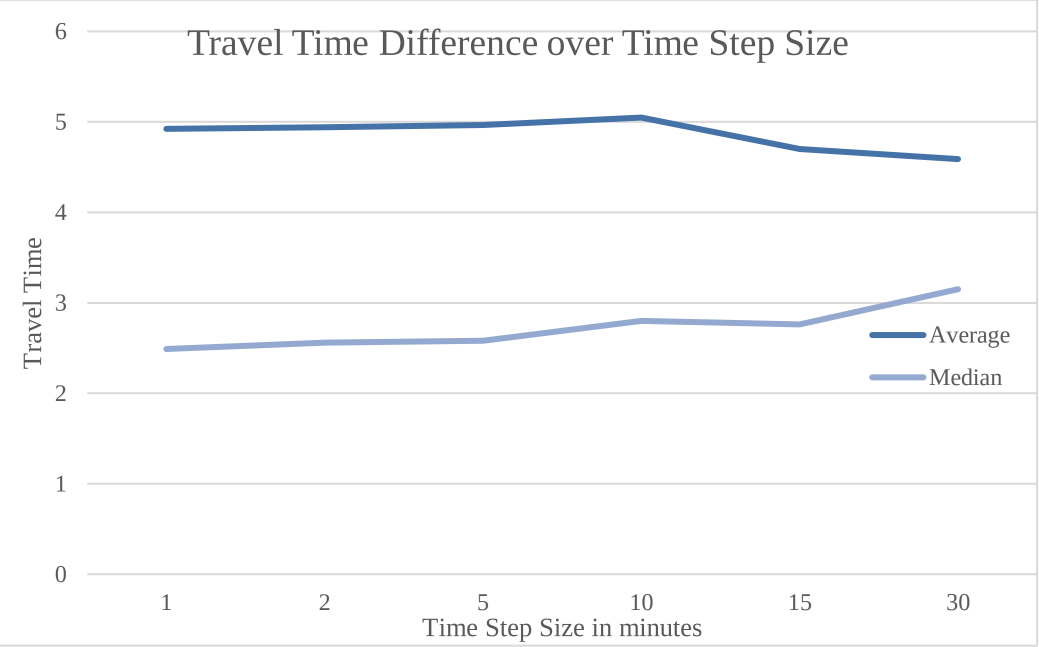

Figure 25: Travel Time Difference over Time Step Size

E.2 branch and bound

In the graphs (Figure 26 and Figure 27) below the results of the sensitivity analysis for branch and bound parameters can be found.

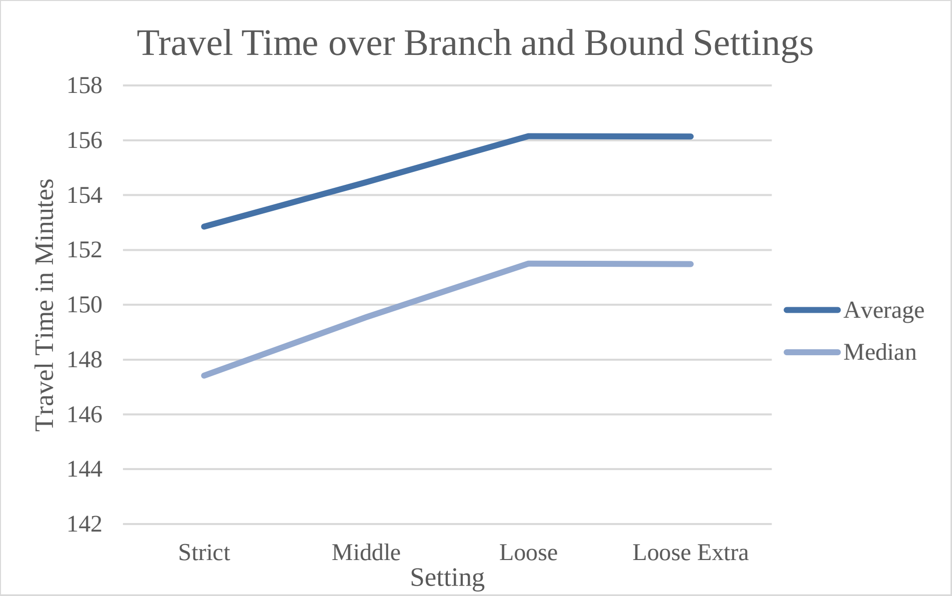

Figure 26: Travel Time over Branch and Bound Settings

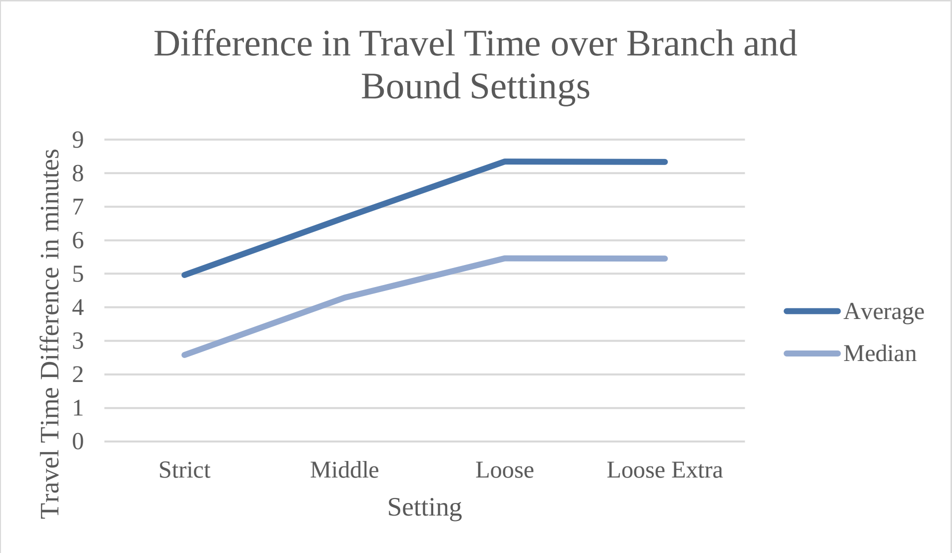

Figure 27: Travel Time Difference over Branch and Bound Settings

E.3 Maximum nr. of transfers

In the graphs (Figure 28, Figure 29 and Figure 30) below the results of the sensitivity analysis for maximum number of transfers can be found.

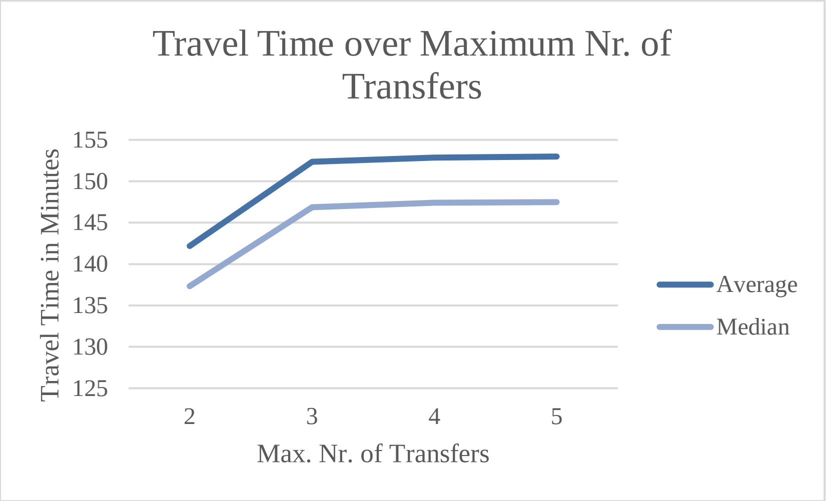

Figure 28: Travel Time over Maximum Number of Transfers

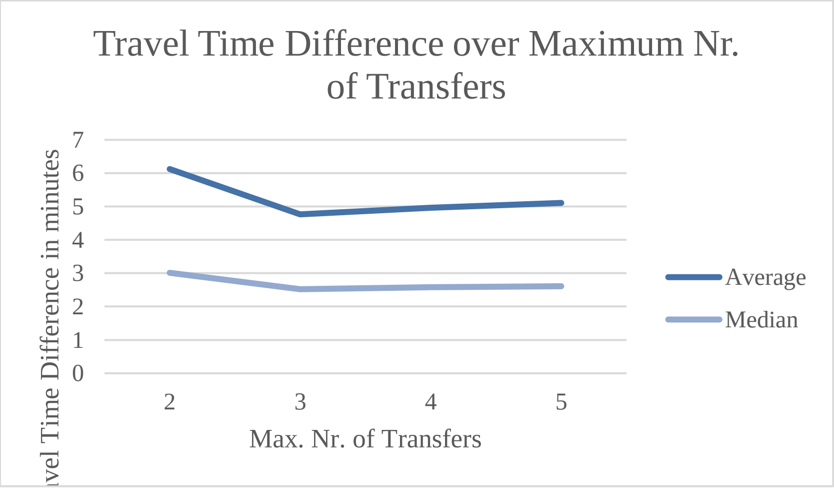

Figure 29: Travel Time Difference over Maximum Number of Transfers

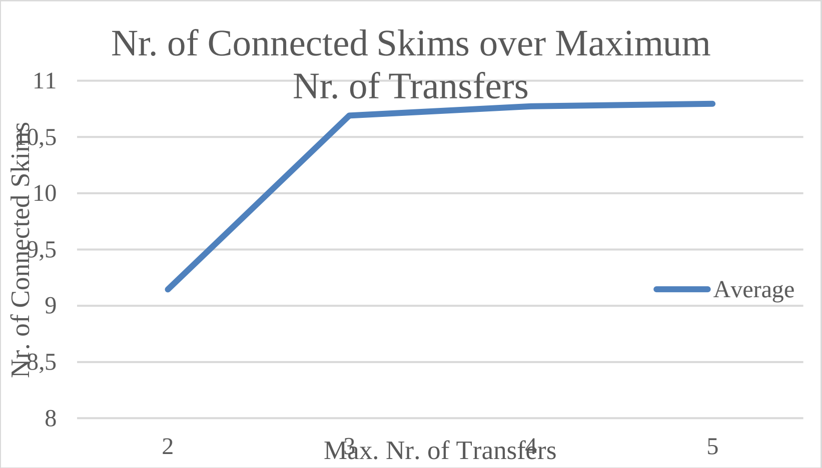

Figure 30: Nr. of Connected Skims over Maximum Nr. of Transfers

E.4 maximum access waiting time

In the graphs (Figure 31, Figure 32 and Figure 33) below the results of the sensitivity analysis for maximum access waiting time can be found.

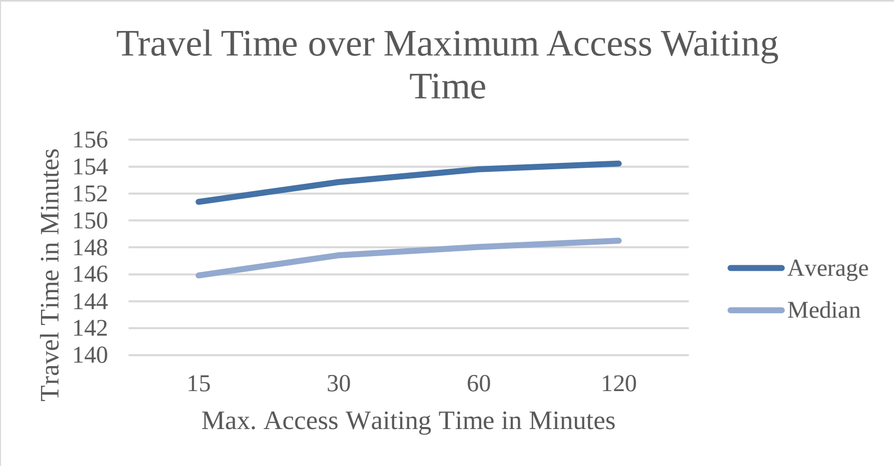

Figure 31: Travel Time over Access Waiting Time

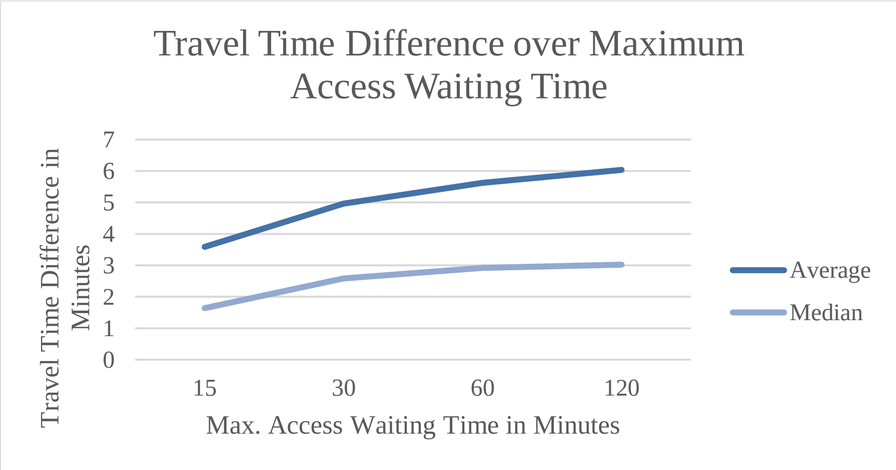

Figure 32: Travel Time Difference over Access Waiting Time

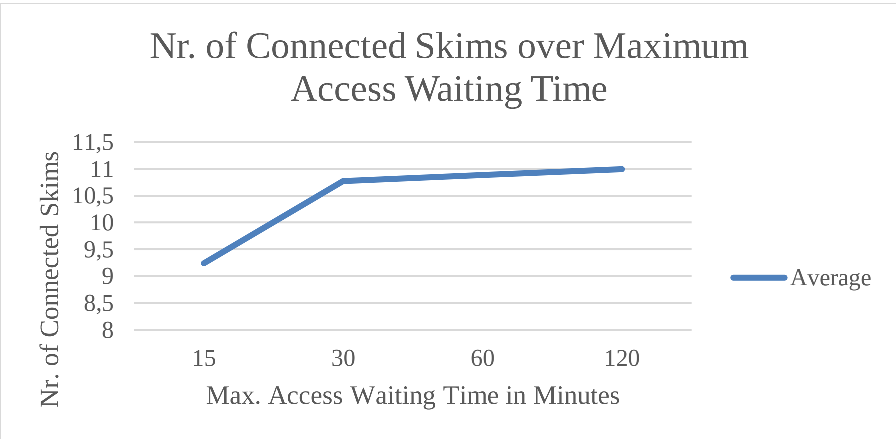

Figure 33: Nr. of Connected Skims over Maximum Access Waiting Time

E.5 minimum nr. of skim values

In the graphs (Figure 34 and Figure 35) below the results of the sensitivity analysis for minimum number of skims can be found.

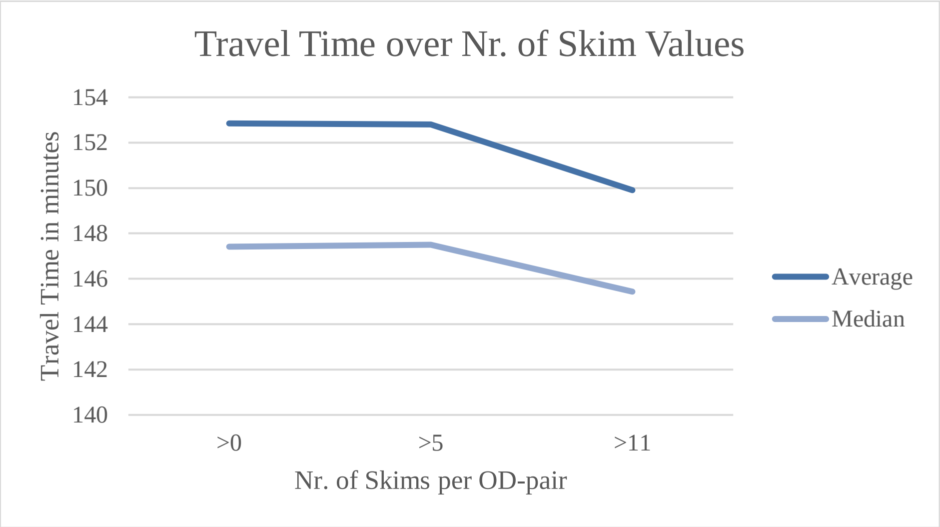

Figure 34: Travel Time over Number of Skims

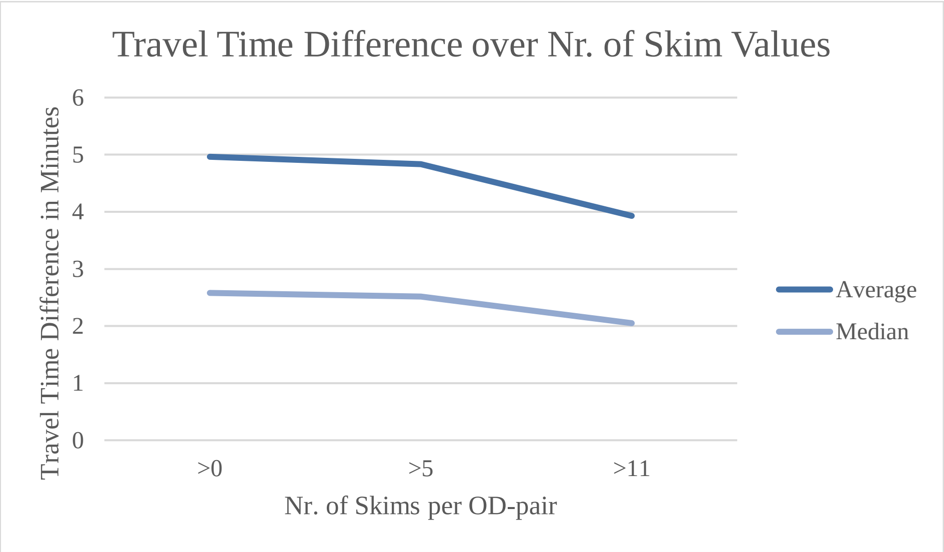

Figure 35: Travel Time Difference over Number of Skim Values

F. Amount of Connected skims

In this appendix the amount of skims that are present after a SB assignment for the National Rail Model are given. This is given to get some more insight in the dataset used to gain the results. In the table below (Table 25) the percentage per bin can be seen and in the graph below (Figure 36) the distribution of the bins is given.

Table 25: Percentage of skims per OD-pair

Skims per OD	Frequency	Percentage
0	6221	4
1	719	0
2	1462	1
3	1121	1
4	1014	1
5	986	1
6	4157	3
7	1340	1
8	2204	1
9	2251	1
10	3115	2
11	2803	2
12	133810	83

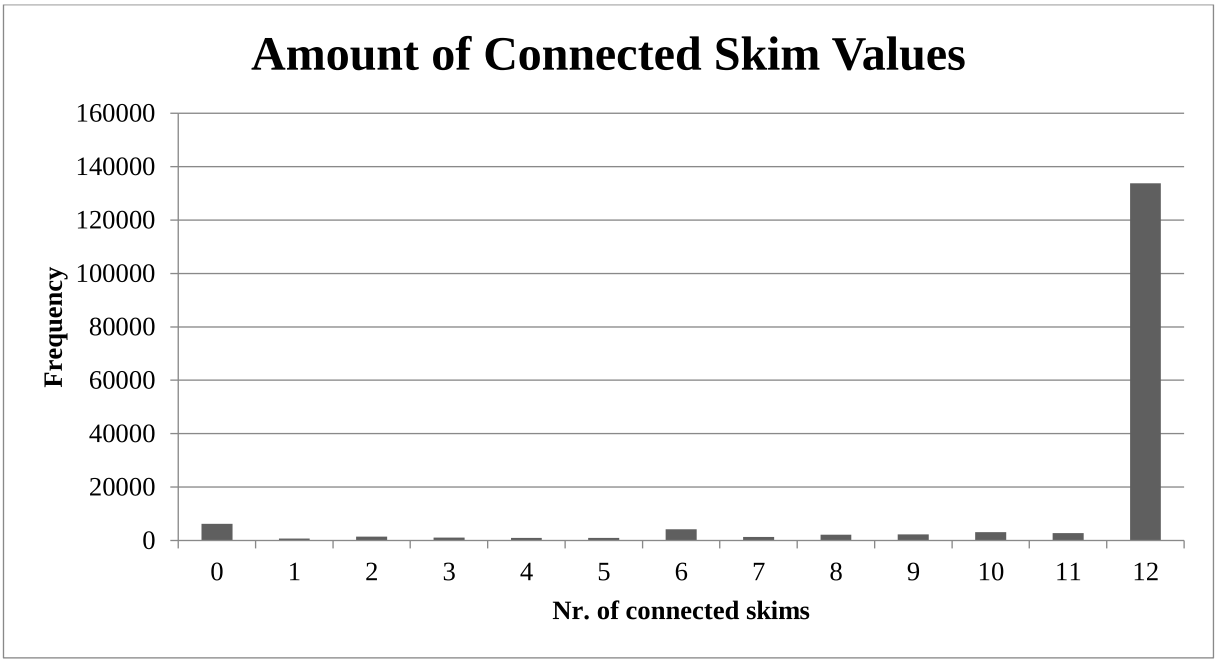

Figure 36: Amount of Connected Skim Values

G. In-Depth Description of an Example

In this appendix an alternating OD relation is elaborated. This helps to get more in depth understanding in the differences between the methods.

Travellers from Enschede to Schiphol Airport can use to logical options. There is a direct connection between centroids Enschede and Schiphol Airport that leaves once every hour from Enschede. There is also a connection that requires passengers to transfer at Amersfoort, to go to Schiphol, which also leaves once every hour from Enschede. This transfer is cross-platform and only takes 2 minutes. Therefore the indirect route takes exactly the same time as the direct route. It is expected that travellers between Enschede and Schiphol will almost only used these two routes and the direct route will be preferred.

Assume that a group of travellers arrive between station Enschede between 07:00 and 08:00 and want to travel to Schiphol Airport. All logical options are shown below(Table 26). Both assignments are done on this time frame. The SB proportions resulting from the assignment can also be found in the table.

Table 26: Results of SB Assignment on Example

Option	Type	Departure time	Average Access Waiting Time (minutes)	In-vehicle Time (minutes)	Proportion SB
Option 1	Direct	07:15	7,5	127	33%
Option 2	Transfer	07:45	15	127	42%
Option 3	Direct	08:15	15	127	25%
Option 4	Transfer	08:45	22,5	127	0%

Overall for a SB assignment 42% of all travellers between Enschede and Schiphol use the route with transfer. 58% of the travellers use the direct connection. The skim results generated from this assignment can be found in the table below.

After a FB assignment the penalty skim was analysed to find out the proportions per type. The total penalty was 1,286 minutes. If 100% of travellers used the route with transfer, the penalty skim would have been 5 minutes. Since 1,286 is 26% of the maximum penalty skim value, it can be said that 26% of travellers use the indirect route. 74% of all travellers use the direct route. The skim value of the FB assignment can be found in the table below (Table 27).

Table 27: Skim Results of Example

Skim Type	SB (minutes)	FB (minutes)
Travel Time	140,6	153,5
Access Waiting Time	13,6	23,6
Transfer Waiting Time	1	3
Penalty	2,2	1,3

From the skim results it becomes clear that the route with transfer is used less as already mentioned before. As can be seen the transfer waiting time is shorter with the SB assignment, this is the expected result. Access waiting times are much longer for the FB approach, since the FB approach prefers the direct route. These longer waiting times result in a higher travel time for this relation. The travel time from the NS application gives 107 minutes. After subtracting the access waiting time from the travel times it is clear that the FB travel time has a higher deviation.

H. Relative Scatter Plot In-Vehicle Comparison

In this section another scatter plot of the in-vehicle travel time over the demand can be seen below (Figure 37).

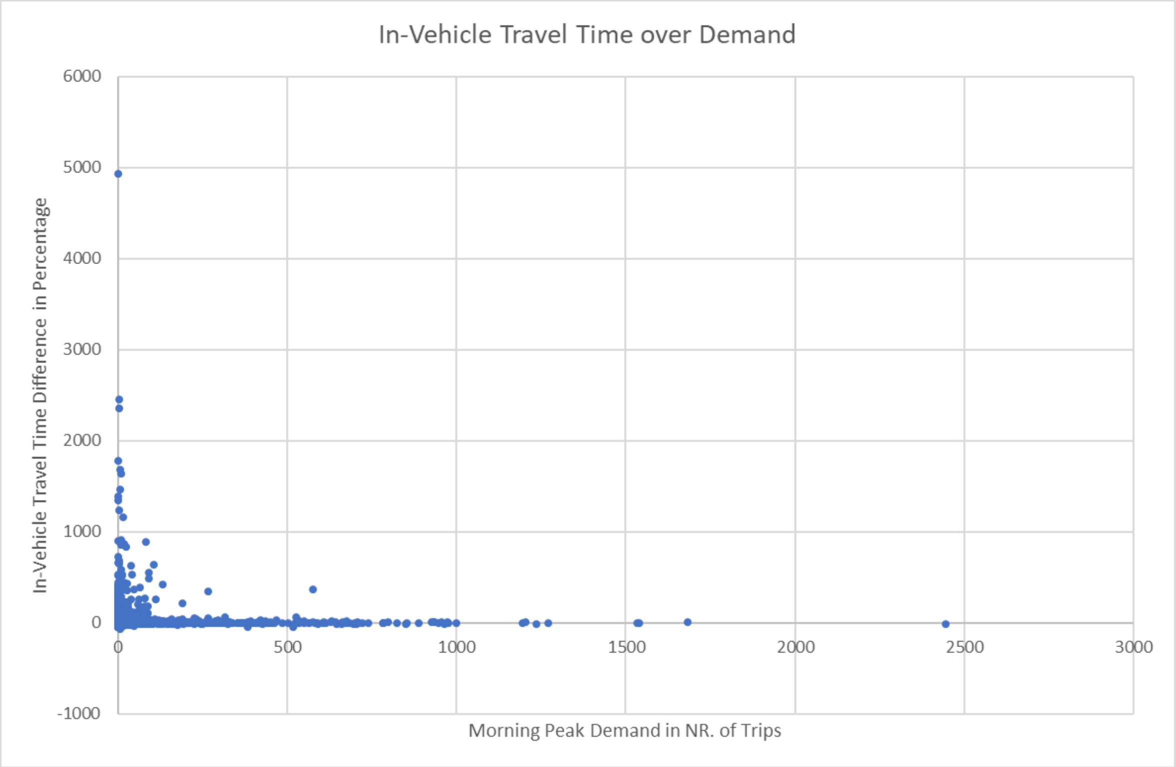

Figure 37: Relative In-Vehicle Travel Time Difference over Demand

I. In-Depth Analysis

In this section of the appendices all used OD-pairs for the in-depth analysis are shown. Skim values per OD-pair can be found in the tables below.

I.1 High frequency

Relations with high frequencies are defined as relations with four or more direct trains per hour. The skim results of the selected routes are shown below (Table 28)

Table 28: High Frequency In-Depth Analysis

High Frequency									
O-D Name	O-D Nr.	Real Time [min]	SB [min]	SB WT [min]	SB Deviation [min]	FB [min]	FB WT [min]	FB Deviation [min]
Den Haag HS - Rotterdam Centraal	297-341	20	26	7	-1	25	3	2
Rotterdam Centraal - Den Haag HS	341-297	19	26	5	1	24	5	-0
Den Haag HS - Leiden Centraal	297-291	13	26	7	6	25	3	9
Leiden Centraal - Den Haag HS	291-297	12	17	5	-	21	8	1
Schiphol - Amsterdam Zuid	230-237	7	10	2	1	11	3	2
Amsterdam Zuid - Schiphol	237-230	6	11	5	-	10	3	1
Utrecht Centraal - Amsterdam Zuid	192-237	22	35	12	1	31	8	2
Amsterdam Zuid - Utrecht Centraal	237-192	22	32	9	1	32	8	2
Average		15	23	6	1	22	5	2

I.2 Low frequency

Relations with low frequencies are defined as relations with less than two direct trains per hour. The skim results of the selected routes are shown below (Table 29).

Table 29: Low Frequency In-Depth Analysis

Low Frequency								
O-D Name	O-D Nr.	Real Time [min]	SB [min]	SB WT [min]	SB Deviation [min]	FB [min]	FB WT [min]	FB Deviation [min]
Groningen - Nieuweschans	22-46	49	74	24	1	62	10	3
Nieuweschans - Groningen	46-22	49	63	17	-3	61	16	-4
Leeuwarden - Stavoren	14-1	54	83	27	1	82	23	5
Stavoren - Leeuwarden	1-14	53	84	31	-	69	20	-4
Gramsbergen - Zwolle	65-70	34	53	18	1	66	30	2
Zwolle - Gramsbergen	70-65	33	47	12	2	64	23	8
Groningen - Winschoten	22-45	34	61	26	1	51	13	4
Winschoten -Groningen	45-22	35	53	18	-	51	16	1
Average		**43**	**64**	**22**	**0**	**63**	**19**	**2**

The first two access waiting times for the FB assignment are remarkable. These access waiting times are low, which suggest another route may be used. This other route can be any route, which departs earlier and uses a transfer to get to the destination.

I.3 Transfer required

These relations with transfers are defined as relations with no direct train connections. The skim results of the selected routes are shown below (Table 30).

Table 30: Transfer Required In-Depth Analysis

Transfer Required								
O-D Name	**O-D Nr.**	**Real Time [min]**	**SB [min]**	**SB WT [min]**	**SB Deviation [min]**	**FB [min]**	**FB WT [min]**	**FB Deviation [min]**
Arnhem Centraal - Apeldoorn	127-83	44	57	7	5	70	10	16
Apeldoorn - Arnhem Centraal	83-127	46	58	8	3	67	10	11
Apeldoorn - Zwolle	83-70	39	59	9	11	57	5	12
Zwolle - Apeldoorn	70-83	38	59	17	5	58	15	5
Groningen - Deventer	22-88	86	100	12	2	111	10	15
Deventer - Groningen	88-22	85	129	25	19	111	15	11
Enschede - Oldenzaal	102-99	23	34	5	6	36	6	8
Oldenzaal - Enschede	99-102	24	38	12	2	37	10	3
Average		**48**	**66**	**12**	**7**	**68**	**10**	**10**

I.4 Alternating

Alternating relations are defined as relations with at least one direct and one indirect connection per hour. If a transfer is needed to reach the destination, depends on the persons departure time. The skim results of the selected routes are shown below (Table 31).

Table 31: Alternating In-Depth Analysis

Alternating (Transfer/Direct)								
O-D Name	**O-D Nr.**	**Real Time [min]**	**SB [min]**	**SB WT [min]**	**SB Deviation [min]**	**FB [min]**	**FB WT [min]**	**FB Deviation [min]**
Enschede - Schiphol	102-230	127	146	18	1	154	24	3
Schiphol - Enschede	230-102	128	153	22	2	154	17	9
Groningen - Schiphol	22-230	127	153	24	2	156	19	10
Schiphol - Groningen	230-22	128	163	23	12	157	12	17
Groningen - Rotterdam Centraal	22-341	157	188	29	2	184	18	9
Rotterdam Centraal - Groningen	341-22	157	187	26	4	183	17	9
Enschede - Den Haag Centraal	102-298	140	169	26	3	157	20	-3
Den Haag Centraal - Enschede	298-102	139	172	31	2	164	16	9
Average		**138**	**166**	**25**	**3**	**164**	**18**	**8**

I.5 Direct

Direct relations are defined as relations where there is a direct connection available and where a route with transfers is much longer. The skim results of the selected routes are shown below (Table 32).

Table 32: Direct In-Depth Analysis

Direct								
O-D Name	**O-D Nr.**	**Real Time [min]**	**SB [min]**	**SB WT [min]**	**SB Deviation [min]**	**FB [min]**	**FB WT [min]**	**FB Deviation [min]**
Zwolle - Deventer	70-88	24	40	17	-1	40	15	1
Deventer - Zwolle	88-70	24	49	25	-	40	15	1
Deventer - Apeldoorn	88-83	10	18	7	1	19	6	3
Apeldoorn - Deventer	83-88	10	19	9	1	18	5	2
Enschede - Almelo	102-96	19	29	7	3	31	7	5
Almelo - Enschede	96-102	19	27	5	4	31	7	6
Groningen - Zwolle	22-70	57	69	11	1	72	10	5
Zwolle - Groningen	70-22	57	77	16	4	72	10	5
Average		**28**	**41**	**12**	**2**	**40**	**9**	**3**

I.6 Short distance

Relations with short distances are defined as relations that are less than 30 km in length. The skim results of the selected routes are shown below (Table 33).

Table 33: Short Distance In-Depth Analysis

Short Distance									
O-D Name	O-D Nr.	Real Time [min]	SB [min]	SB WT [min]	SB Deviation [min]	FB [min]	FB WT [min]	FB Deviation [min]	
Enschede - Almelo	102-96	19	29	7	3	31	7	5	
Almelo - Enschede	96-102	19	27	5	4	31	7	6	
Zwolle - Deventer	70-88	24	40	17	-1	40	15	1	
Deventer - Zwolle	88-70	24	49	25	-	40	15	1	
Deventer - Apeldoorn	88-83	10	18	7	1	19	6	3	
Apeldoorn - Deventer	83-88	10	19	9	1	18	5	2	
Zwolle - Kampen	70-71	10	22	13	-1	25	15	0	
Kampen - Zwolle	71-70	10	26	16	-	26	15	1	
Average		**16**	**29**	**12**	**1**	**29**	**11**	**2**	

I.7 Long distance

Relations with long distances are defined as relations that are more than 200 km in length. The skim results of the selected routes are shown below (Table 34).

Table 34: Long Distance In-Depth Analysis

Long Distance								
O-D Name	O-D Nr.	Real Time [min]	SB [min]	SB WT [min]	SB Deviation [min]	FB [min]	FB WT [min]	FB Deviation [min]
Gronigen - Maastricht	22-419	252	285	29	4	272	17	-9
Maastricht - Groningen	419-22	251	262	15	-4	266	12	1
Maastrcht - Den Helder	419-261	236	244	15	-7	248	12	-3
Den Helder - Maastricht	261-419	224	247	13	10	245	17	8
Vlissingen - Leeuwarden	361-14	292	329	30	7	304	15	-18
Leeuwarden - Vlissingen	14-361	292	294	17	-16	253	15	-56
Den Helder - Enschede	261-102	208	240	14	18	231	10	8
Enschede - Den Helder	102-261	221	249	27	1	235	11	-13
Average		**247**	**268**	**20**	**2**	**257**	**14**	**-10**

As can be seen from the relation: Leeuwarden – Vlissingen, there is a large difference between the modelled times and the ‘real time’. This difference is caused by a change in schedule for this OD-pair.