Developing a model for finding promising Bus Rapid Transit corridors between city zones

Bachelor Thesis

Luuk Spijker

06-06-2024

Bachelor Thesis

Developing a model for finding promising Bus Rapid Transit corridors between city zones

Luuk Spijker

6-6-2024

Institution:	University of Twente
Study:	Bachelor Civil Engineering
Student number:	s2514206
Contact:	l.m.spijker@student.utwente.nl
Internal supervisor:	A. (Alejandro) Tirachini PhD
Company:	Keypoint Consultancy
Adress:	Institutenweg 32, 7521 PK Enschede
External supervisors:	C. (Cees) Bakker, J. (Justin) van Steijn

Preface

You are currently reading my Bachelor Thesis “Developing a model for finding promising Bus Rapid Transit corridors between city zones”, which I have carried out over the course of ten weeks at Keypoint Consultancy in Enschede. With that, I want to thank Keypoint Consultancy for welcoming me and supporting me, in particular my supervisors Cees Bakker and Justin van Steijn. During my time at the company I have learned a lot about consultancy in the mobility sector, something which I may want to pursue in my further career.

Besides that I want to express my gratitude towards my supervisor from the University of Twente, Alejandro Tirachini. I want to thank Alejandro for his support and knowledge about public transport and academic writing.

This thesis project taught me how to collaborate with my supervisors, but also how to do research and apply tools like Python. I am grateful to have had this opportunity.

With that, my Bachelor Civil Engineering at the University of Twente comes to an end and I am eager to see what is next.

Luuk Spijker

20th of June 2024

Abstract

The possibility of implementing Bus Rapid Transit within The Netherlands has been a topic of discussion for quite some time already. BRT is a form of Hoogwaardig Openbaar Vervoer (HOV, 'high-quality public transport'), a mode of transport which conforms to high quality and frequency standards. BRT could be introduced to the public transport network with the aim to increase mobility and decrease car dependency within The Netherlands.

While certain corridors are already being explored, there currently exists no model which automates the search for promising BRT corridors on a smaller, and thus more detailed, scale than municipality scale.

The model developed and tested in this thesis finds promising BRT corridors between 4-number postal code zones. This scale is small enough to divide cities in smaller parts, which means that corridors between city zones can be found. The model uses population, number of jobs, great-circle distance and difference between car and public transport travel time as factors for assigning a BRT Score to each origin-destination pair. The results are then displayed in a figure. On top of that, a web application was developed to interactively show the results. It was found that around Schiphol and The Hague, multiple promising BRT corridors are located.

This research not only aims to develop and test a general model for finding promising BRT corridors, the aim is also to find a method for developing a complete BRT route with intermediate stops. This was achieved by finding the population centers of zones within a certain buffer between the origin and destination and applying Dijkstra's algorithm for finding the shortest path between these. On top of that, a method was developed to find the most efficient stop selection by making a consideration between travel time and BRT Score.

Finally, a case study for Schiphol Airport was developed. To account for people travelling to Schiphol for both flying to/from the airport and people working at the airport, a formula for calculating the BRT Score was developed. Within the top ten, corridors between Schiphol, Leiden, Alphen ad Rijn and Hoofddorp came forward as the most promising locations for BRT systems.

Table of contents

1. Introducton

The history of mass transit within cities starts off with the most simple form of getting around: walking. Later, animals like horses used to carry humans around, followed by animal-drawn carriages carrying multiple people. Steam powered trains, combustion engine buses and electric trolleys only came into existence by the late 19th century (Schofer, 2024). The reasons of getting around were to buy groceries at the local market, getting to work at the factory, getting to school or visiting relatives.

Nowadays, in The Netherlands, different forms of urban public transport exist; bus, tram, metro and even boat. However, the objectives for travel largely remained the same, but in a modern form. Reason to travel is known as travel demand, and depends on factors such as demographics, economics, prices, transport options, service quality and land use (*Online TDM Encyclopedia - Transportation Demand*).

A particular form of public transportation is Bus Rapid Transit. The Kennisinstituut voor Mobiliteitsbeleid (2020) describes BRT as “a bus system that operates at high frequency and speed”, and “is highly reliable as a high-quality transport product”. Given the properties of BRT, it may function as an important link in the public transport network.

This thesis is a continuation of the thesis by de Wit (2023) performed at Keypoint Consultancy. De Wit is a fellow civil engineering student who successfully constructed a framework for finding promising BRT routes between municipality centres. The next step for this model is to zoom in on a smaller scale, in order to find promising connections between city zones.

This thesis starts off with describing the problem context behind this research, followed by a theoretical framework which summarizes knowledge about BRT, demand analysis and network design. Then, the research objectives and questions are stated, after which the research methods are described per research question. This is followed by the research results and discussion, which are also in order of research question. The report finishes with a final conclusion and recommendations for further studies.

2. Problem Context

In this chapter, background about this research will be given. Starting with the involved parties, research motivation and problem statement, and discussing the study area and previous studies about Bus Rapid Transit within The Netherlands. On top of that, the research aim, research scope and research questions will be stated.

2.1 Involved parties

The commissioner of this thesis is Keypoint Consultancy. With their motto ‘Smartly forward together’, Keypoint combines technology and data to solve problems regarding mobility for other parties, like municipalities. My external supervisor at Keypoint is Cees Bakker, team manager mobility within the company. Justin van Steijn, advisor mobility within the company, will assist with the technical aspect of my assignment. The desire of Keypoint is to receive research on Bus Rapid Transit on a local scale which is easy to repeat for other situations. This information can then be shared with their clients. The specific objective is to look at the possibilities of BRT between city zones in The Netherlands, especially in the Randstad and around Schiphol.

2.2 Research motivation

The motivation behind this research is to explore BRT possibilities in The Netherlands further. The reason for exploring BRT is that this form of transport currently is not very common in The Netherlands, so the potential for application might exist. The motivation behind this is to expand the Dutch public transport network, in order to increase mobility and ultimately reduce car dependency.

2.3 Problem statement

In the current public transport system, transfers at central train stations to travel from door to door are common. Direct connections between specific parts of two different cities other then their central train station are not common, thus requiring more transfers and likely a higher travel time between these city zones. BRT could offer more direct routes leading to less transfers, but there currently does not exist a general method of finding promising BRT corridors on a local scale. On top of that, no model for finding suitable BRT routes exists yet which incorporates local public transport options. However, only finding promising BRT corridors between neighbourhoods may not lead to a successful BRT line on itself. A bus, metro or tram line runs through the city and has multiple intermediate stops. This can be compared with lacing pearls on a wire; together they form a necklace.

According to the Partnership of Decentralised Public Transport Authorities in the Netherlands (Samenwerkingsverband van decentrale ov-autoriteiten – DOVA), around 80% of employees at Schiphol Airport commute by car. Offering better connections with help of BRT may decrease car dependency, but the problem is that it is not known where around Schiphol, on a local scale, demand is present for BRT corridors.

2.4 Study area

The initial study area will be the Randstad (Figure 1). The Randstad is a concentrated urban area in the west of The Netherlands consisting of the cities Amsterdam, Rotterdam, The Hague, Leiden, Utrecht and more[1]. The exact boundaries of the Randstad are hard to define, but the biggest cities of the provinces South-Holland, North-Holland and Utrecht are included at least. A large urban area asks for high capacity and frequent mobility solutions, which BRT may provide.

Figure 1: the Randstad. The "Green Heart" is given in light green and the Schiphol area in dark green

The study could be applied to the whole of The Netherlands. However, since The Netherlands can be split up into many city zones, a big number of origin-destination pairs can be generated. Due to computational limitations, this study area could be deemed impossible. Therefore the Randstad will be the primary study area.

A special area within the Randstad is Schiphol Airport. While Schiphol is not an urban area, it also asks for frequent and high capacity mobility. Schiphol is the primary airport of The Netherlands and functions as an important hub for national carrier KLM. Handling 70 million passengers yearly, Schiphol ranks as third busiest airport of Europe (Amsterdam Airport). Besides attracting many travellers, Schiphol is also a large employer in the Amsterdam region. Around 65.000 people are employed at Schiphol Airport or at the companies located around the airport. All these travellers and employees have to get to and from Schiphol.

Currently, Schiphol is connected by national and international trains, buses, and the highway A4 (Amsterdam Airport). Although the public transport connection seems well, around 80% of employees around Schiphol still arrive by car. This is why Schiphol is an interesting case for exploring BRT opportunities, although not being an urban area itself.

[1] https://www.plaatsengids.nl/randstad

2.5 Previous studies

De Wit (2023) successfully developed a framework for finding promising BRT routes between municipality centers using a gravity model. Next to using a gravity model, other criteria were determined to find suitable OD-pairs. For example, an exponential decay function was used to determine attractiveness of job opportunities as a criterium. Promising routes are then ranked according to these different criteria, taking into account existing PT networks like train, metro or tram. However, existing bus routes are not taken into consideration automatically, this was done manually after a promising route was found.

DOVA has a collection of research done about BRT in The Netherlands. DOVA is a collaboration of the 12 provinces, Vervoerregio Amsterdam (Transport Region), the Metropoolregio Rotterdam Den Haag (Urban Region) and the OV Bureau Groningen Drenthe (DOVA, 2024). Their goal is to form a common policy regarding PT and produce and share data about PT in order to improve PT in The Netherlands.

One of these research projects is performed by Jakobs et al. at the University of Applied Sciences Windesheim (2019). Jakobs et al. addressed a similar problem as described in chapter 2.3, namely transfers at central train stations adding to the total travel time. They tackled this problem by forming a 'river delta' system, where two hubs at the edge of the city would be connected by a corridor and from the hubs multiple lines spread over the city. Since these would have a high frequency, transfer times would be short and the busy city centers would be avoided (Figure 2).

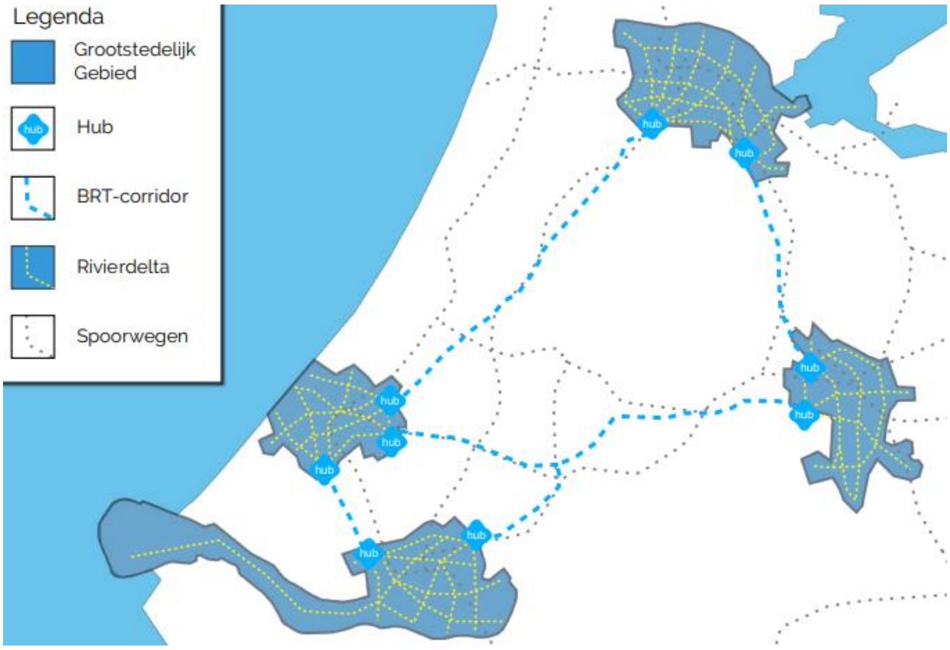

Figure 2: 'river delta' model concept. Translations: grootstedelijk gebied = metropolitan area, rivierdelta = riverdelta, spoorwegen = railways

2.6 Research aim

The aim of this research is to create a model for finding promising BRT corridors between city zones. On top of that, the aim is to find out how to connect multiple city zones in one line, like the pearls on a necklace, in order to make a line more successful.

2.7 Research scope

The geographical scope of this research is city zones within the Randstad. Schiphol Airport will be included as a case study. At this scale level, inter-city BRT is the corresponding system type. In my research, international BRT is neglected.

Besides that, the research revolves around building a model for assigning a suitability score for BRT within a specific study area. This means that the research does not explicitly tell anything about absolute travel demand, since data about travel behaviour is not applied in this research. The research is limited to using a gravity model including population and job data, car and public transport travel time, and great circle distance. On top of that, more details about promising BRT corridors like frequency, costs, ridership and specific infrastructure is not included in this research.

2.8 Research objectives and research questions

Research objectives:

- To construct a model for finding promising Bus Rapid Transit routes between city zones in the Randstad area
- To connect multiple city zones together to form a promising BRT line
- To work out a case study for Schiphol Airport based on the developed model

Research questions:

- What factors determine BRT travel demand between zones?
- What do the zones look like which make up origins and destinations?
- What are promising BRT corridors within the study area?
- In what way can intermediate stops be included in the model?
- What are promising BRT corridors to and from Schiphol?

3. Theoretical framework

In this chapter, a collection of key concepts about Bus Rapid Transit, demand analysis and network design will be explored.

3.1 Definition of BRT

Bus Rapid Transit is a high capacity bus system which can be related to a metro. It achieves this high capacity by the use of dedicated bus lanes and a high frequency. A quick boarding process is crucial for achieving a high reliability and frequency (ITDP, 2018). Criteria for successful BRT are discussed in chapter 3.3.

BRT systems are common in high density urban areas, where the cost of constructing a metro network is not feasible. BRT can function as a cost effective solution for implementing a public transport system. On top of that, it can be set up relatively quick compared to building a metro network. Currently, 191 cities have a BRT-like system in their public transport network with a daily ridership of around 31 million people[2].

A successful example of BRT is TransJakarta in de Indonesian capital Jakarta (Figure 3). With a population of over 10 million people, the demand for public transport is big. Unlike European cities, Jakarta has started construction on a metro network very late; in 2019 the first line was opened. Due to the speed of implementation and reduced costs, Jakarta focused on BRT and now has the longest network of dedicated bus lanes in the world (ITDP, 2018).

Figure 3: TransJakarta

In Europe, systems considered as BRT exist as well. However, most of them do not reach ridership numbers as high as systems found in Asia or South America. An example of a successful BRT system in Europe is the Trans-Val-de-Marne (Figure 4), in the outskirts of

[2] https://brtdata.org/

Paris. Buses run every 5 minutes, which can be considered high frequency. The line consists of mostly dedicated bus lanes, and are served by low floor buses[3].

Figure 4: TvM bus on its dedicated bus lane

3.2 Variations of BRT-like systems in The Netherlands

A study conducted by the Dutch Ministry of Infrastructure and Waterworks (2019) identified 4 different BRT-like systems in The Netherlands, each on a different scale. These are the following:

- **Intra-city BRT.** These are high frequency connections within urban areas. They mainly function as feeders for national rail networks. A quick boarding process and separate bus lanes are a necessity. Examples in The Netherlands include R-Net Eindhoven, Q-Link Groningen or U-Link Utrecht.

- **Inter-city BRT**, functioning as rail support. This means that these BRT lines run along corridors which are already served by a train route, however this train route may have reached capacity and a BRT route can help relieve the pressure, especially in peak hours. On top of that, trains mainly connect centres of cities while rail supporting BRT may connect suburbs with other suburbs and city centres. Comfort, speed and a right of way are a necessity. Examples in The Netherlands include Q-Liner Assen-Groningen and R-net Amsterdam-Haarlem.

- **Inter-city BRT**, along corridors where no rail route exists. These BRT routes function as a backbone for connecting cities which do not have a rail connection, and mainly use highways and provincial roads as route. Comfort, speed and a right of way are a necessity. Examples in The Netherlands include Emmen-Groningen, Breda-Utrecht and Zeeland-Rotterdam.

[3] https://www.ratp.fr/

- **International BRT**, connecting cities across the border. They function as intercity BRT, either rail or non-rail supporting, but with a lower frequency and on longer distances. Comfort is the main necessity. Examples in The Netherlands include Flixbus and Maastricht-Hasselt.

The research by the Ministry shows that BRT-like systems already do exist in The Netherlands, and function on different scales.

3.3 Criteria for successful BRT

To make BRT successful, the Kennisinstituut voor Mobiliteitsbeleid (2022) has set up multiple criteria that have to be met. These are grouped per stakeholder: the operator, the passenger and society.

From an operator's perspective, these are the criteria for success for BRT:

- Right of way. Intersections influence the speed and reliability of BRT. BRT should get right of way at intersections in the form of smart traffic lights or even controlled moving barriers.
- Ticketing at the stop and not in the bus. According to Tirachini (2013), ticketing systems outside the bus decrease dwell time. Prepaid cards validated inside the bus can lead to intermediate dwell times while cash payments within the bus may lead to the longest dwell time.
- Dedicated bus lanes. To increase the speed and efficiency, BRT should be separated from normal traffic, especially on busy corridors.

From an passenger's perspective, these are the criteria for success for BRT:

- Comfortable and (socially) safe stops. Waiting times weigh 1,75 to 2 times more than travel time in the vehicle. This can increase to even 4 times when the waiting area is uncomfortable, according to the Kennisinstituut voor Mobiliteitsbeleid (2022).
- Good communication and information technology. Passengers should be updated real-time about delays, both at the stops and in travel apps.
- Good quality buses with low entrance. According to Tirachini (2013), buses with steps at the entrance increase dwell time while low floor buses lead to decreased dwell times. This also improves accessibility.
- Branding. BRT buses and lines should be visible as a separate brand, in order to distinguish themselves from regular buses or trains. Regular bus systems are sometimes seen as complicated, the BRT system must be simple.
- Transfers at train stations. The BRT system should not be a lone-standing service, but should be incorporated in the entire transport system. Stops at park and ride locations are to be considered as well.
- Professional staff. This will improve branding and shows luxury and give a welcoming image. This may increase passenger satisfaction.

- High frequency service. This means, a bus every ten minutes or even more often. The goal is to travel without a schedule, so getting on at every moment. This also reduces waiting times at transfers.
- Extended service hours. Buses should start operating early in the morning and stop service late in the evening. Some metro systems even provide a 24 hour service.
- Reliability. Delays are perceived as 3 to 5 times longer than actual travel time. A high frequency service can reduce passenger dissatisfaction when delays are present.
- Travel comfort. The buses should reduce lateral movement and avoid fast deceleration and acceleration. On longer distances, seating should be comfortable and provide a table for working with a laptop.

From society's perspective, these are the criteria for success for BRT:

- Clean and silent buses. Electric or hydrogen buses are considered the best options.
- Commitment by policy makers. (Light) rail systems are still favoured by policy makers as they have a better perceived image, even when BRT could be a better solution. Another example is giving up a road lane for a dedicated bus lane, which policy makers find hard to justify to the public.

3.4 Demand Analysis

According to chapter 4 of the BRT Planning Guide developed by the ITDP (2018), a demand analysis is critical for creating a successful BRT network. The guide gives as example that it is tempting to construct a BRT line on a wide highway where there is plenty of space, but where demand is actually limited. The first use of demand analysis is to find out where the public transport demand is concentrated and from that extrapolate where the biggest BRT demand is. According to the guide it is crucial to take into account the current public transport situation to see where BRT can actually make a difference.

To gain insight into how and where people travel, analysing the existing public transport can be helpful. A new BRT system will likely change the way people travel. To see if this change is positive or negative, the pattern of trips, origin-destination pairs and volumes need to be studied. To exactly determine where people want to go, unrelated to their mode of travel, an origin-destination matrix must be developed, which shows the trip distribution for every origin and destination pair. The BRT Planning Guide suggests that surveys are the main method of finding out where people want to travel. However, this usually does not reveal any underlying motivations of why people travel there exactly, so this does not help for finding transport demand factors.

Also, modal shift plays a role. Modal shift is the term for the shift between travel modes, such as train or car. The guide states that a shift to BRT is possible if the attraction is big enough. The attractiveness is highly influenced by the success factors discussed in chapter 3.3. Modal choice is a simple equation; if one mode offers more benefits then the other the first will be chosen. However, this choice is different for every origin-destination pair.

To generate a reasonable estimate of demand for BRT, the following set of data must be collected (ITDP, 2018):

- The routes of current public transport services; these can be mapped in GIS, transport modeling software, or Google Earth or Google Maps;
- The number of travellers using key corridors by means of bus-route-frequency counts and visual-occupancy surveys;
- Bus frequency, preferably for every public transport route in the city, by direction, and in morning and evening peak periods;
- Bus speeds for each road section covered by a potential BRT route;
- Speeds of other vehicles on the existing road network;
- Boarding and alighting surveys (and supplementary spot counts at bus stops), to get a first impression of demand patterns.

Konečný et al. (2021) identified the most important factors for transport demand and evaluated the correlation between these factors and transport demand using the method of correlation analysis. The most important factors include:

- Price of the service
- Quality of the service, such as travel time, frequency, safety, reliability
- Price and quality of alternative modes
- Population and age of potential customers
- Income of potential customers
- Employment rate
- Habits and preferences
- Population density and distribution

The correlation analysis showed that demographics play an important role in transport demand, therefore the study resulted in the development of a regression model for students and working population, and a model for pensioners.

Gamas et al. (2006) developed a method of estimating trip generation in Mexico City. The research shows that the main factors which make up 40% of the total daily trips are work trips, shopping trips and school trips. These amount of trips depend greatly on spatial factors such as density.

Armstrong (2021) researched factors influencing urban public transport within the United States, and identified that these can be distinguished between internal and external factors. Internal factors include transit fares, frequency and travel times. External factors include geographic and socioeconomic characteristics. It was found that both a model for transit supply and transit demand must be developed to get an insight into total demand for new connections.

The TDM Encyclopaedia (2015) developed a table including factors which affect transport demand. These factors where found to fall within one of six categories.

Table 1: Factors which affect transport demand

Demographics	Economics	Prices	Transport Options	Service Quality	Land Use
Number of people (residents, employees and visitors). Incomes Age/lifecycle Lifestyles Preferences	Number of jobs Incomes Business activity Freight transport Tourist activity	Fuel prices and taxes Vehicle taxes & fees Road tolls Parking fees Vehicle insurance Public transport fares	Walking Cycling Public transit Ridesharing Automobile Taxi services Telework Delivery services	Relative speed and delay Reliability Comfort Safety and security Waiting conditions Parking conditions User information Social status	Density Mix Walkability Connectivity Transit service proximity Roadway design

3.5 Gravity model for transport

Different factors can be combined to estimate the total trips made between an origin and destination. A main formula for this is the gravity model (Princeton University, 2008). It is based on Newton's principle of attraction. It states that two objects pull towards each other. How larger the objects, how larger the pull. Also, the smaller the distance between the objects, the larger the pull. In the gravity model for transport, the objects are replaced with population trip production and trip attraction, and intermediate distance or travel time as cost factor.

The gravity model for trips looks as follows:

$$T_{ij} = \frac{A_j * F_{ij} * K_{ij}}{\sum_{x=1}^{n} A_X * F_{ij} * K_{iX}} * P_i$$

Where:

T_{ij} = trips produced at I and attracted at j

P_i = total trip production at i

A_j = total trip attraction at j

F_{ij} = cost factor such as travel time or distance in the form of $F_{ij} = \frac{c}{t_{ij}^{n}}$

K_{ij} = a socioeconomic adjustment factor

n= number of zones

3.6 Characteristics of a BRT line

The database Global BRT Data gives great insight into existing BRT systems and their characteristics. Table 2 gives the average length, amount of stops, and average distance between stops for every BRT system in the world.

Table 2: Average length, amount of stops and stop distance for BRT systems in the world

Average line length (km)	13,3
Average amount of stops per line	16,5
Average distance between stops (m)	811

When only taking BRT systems within Europe, the results are as follows.

Table 3: Average length, amount of stops and stop distance for BRT systems in the world

Average line length (km)	14,6
Average amount of stops per line	22
Average distance between stops (m)	661

3.7 Network design

The planning and design of an urban transit network, can be divided into five main stages: network design, frequency setting, timetable development and bus and driver scheduling (Svensson, 2020).

An optimal network for the operator and environment would be to minimize the total distance of the bus routes, whilst still maintaining the minimum requirements regarding demand and accessibility. On the other hand, an optimal solution for the passengers would be to have an as efficient ride as possible, so minimizing their travel time. Heuristic models are commonly used to create bus routes and combine them into networks based on demand and distance.

Network design is complex and involves many factors. According to Desaulniers and Hickman (2007), a skeleton of routes is constructed using heuristic techniques, after which the frequencies are determined by minimizing total passenger travel time.

When trying to form a route out of a reasonable amount of nodes, without including setting frequencies, Dijkstra's algorithm of finding the shortest path (Figure 5) can be applied. The algorithm starts by evaluating the starting node and assigning it a distance of 0. It then evaluates each of the neighbouring nodes and calculates the distance to each node. The algorithm selects the node with the smallest distance and adds it to the list of visited nodes. It evaluates the neighbouring nodes of the newly added node and calculates their distances. It adds the node with the smallest distance to the list of visited nodes and continues this process until it reaches the destination node (Scientist, 2023).

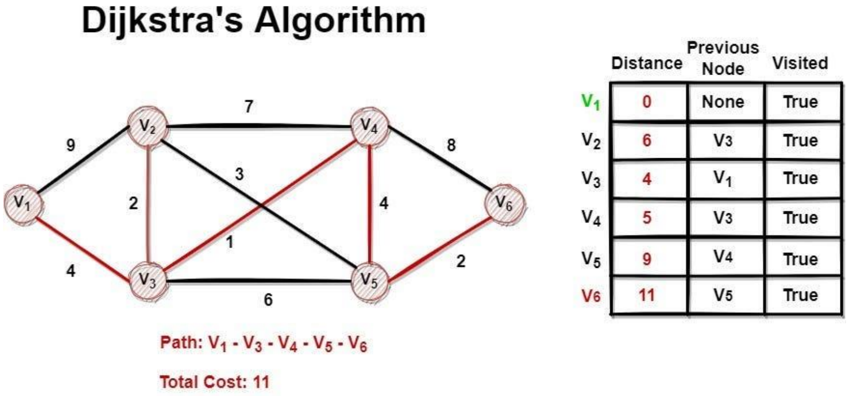

Figure 5: graphical representation of Dijkstra's algorithm

The data necessary for any approach to solve the network design problem are the demand and the distance between nodes, in this case being stations. Note that Dijkstra's algorithm only incorporates distance and not demand between nodes. The demand could be given as amount of passengers needing to get to certain areas from other areas. In the case of de Wit his thesis, a gravity model was used to determine this travel demand.

4 Method

In this chapter, the method used for finding an answer to the research questions will be discussed.

4.1 Determining the factors for BRT corridor demand

To determine which factors make up demand for BRT corridors, a literature study was conducted, which can be found in the Theoretical Framework. Factors for general travel demand for public transport have been researched.

Besides the factors determining travel demand, the ideal length of a BRT line was also explored with this literature review.

4.2 Defining the origin-destination zones

In order to build a model for finding promising BRT connections between city zones, the city zones functioning as origins and destinations had to be defined first. It was determined that the city zones had to comply with the following conditions:

1. The size of the city zones should be the size of a city neighbourhood
2. The zones must be connected to a database which contains sufficient data for use in the estimation of travel demand
3. City zones and their data must be available for the whole of The Netherlands

To comply with condition two and three, it was chosen to refer to a database which provides the necessary data for different levels of scale, and for the whole of The Netherlands. To comply with the condition that geometry data must be available for each zone, a suitable file type was looked for which supports this type of data. When a suitable database was found, a level of scale was chosen which complies with condition one.

It was determined that the model has to process this data in the following ways:

1. Create a map with all city zones within the chosen study area
2. Show on this map the population center of each city zone, to represent where most people live. Distances and travel times will be calculated between these points
3. Create a table with the following columns: name of the city zone, population of this zone, amount of jobs in this zone, the polygon shape of this zone, and a specified centerpoint of this zone

To achieve objective one, code was written which interprets the geometry data of each city zone and draws the borders of each city zone within the study area on a map background retrieved from OpenStreetMap.

To achieve objective two, namely finding a centerpoint of each zone, the population center was chosen to represent this centerpoint. To find the population center of each city zone, the principle of finding the center of gravity was used. This principle tells that a plate consisting of smaller planes each with their own weight and center of gravity can be combined to find the total weight and total center of gravity. See Figure 6 for a visualisation of this principle.

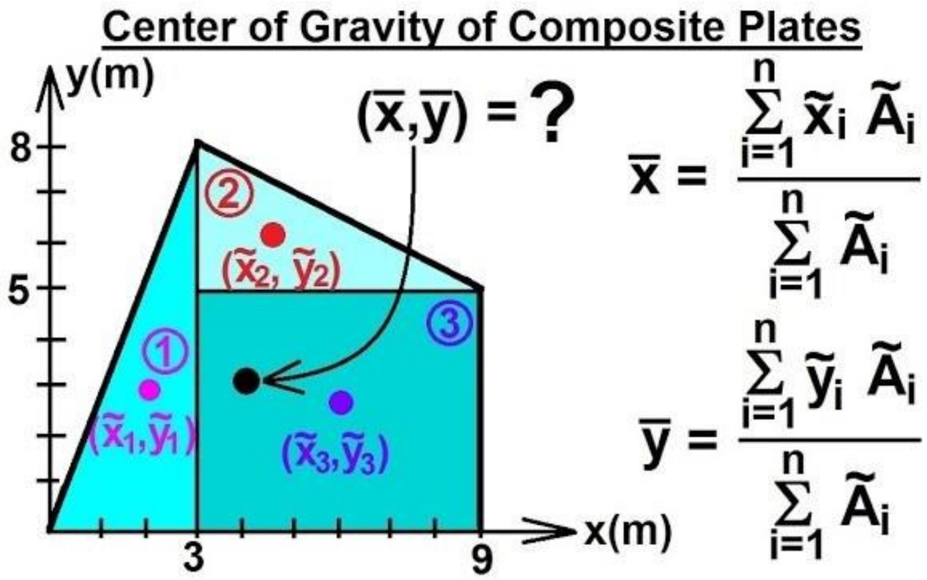

Figure 6: graphical representation of finding the center of gravity of a plate (van Biezen, 2016)

This principle was applied for finding the population center by considering population of each 5-number postal code as ‘weight’ and the centroid of each 5-number postal code as ‘center of gravity’. In terms of city zones, this meant breaking down each city zone into smaller city zones and applying the principle. An example of how a 4-number postal code zone was broken down in their 5-number postal code zones can be seen in Figure 7.

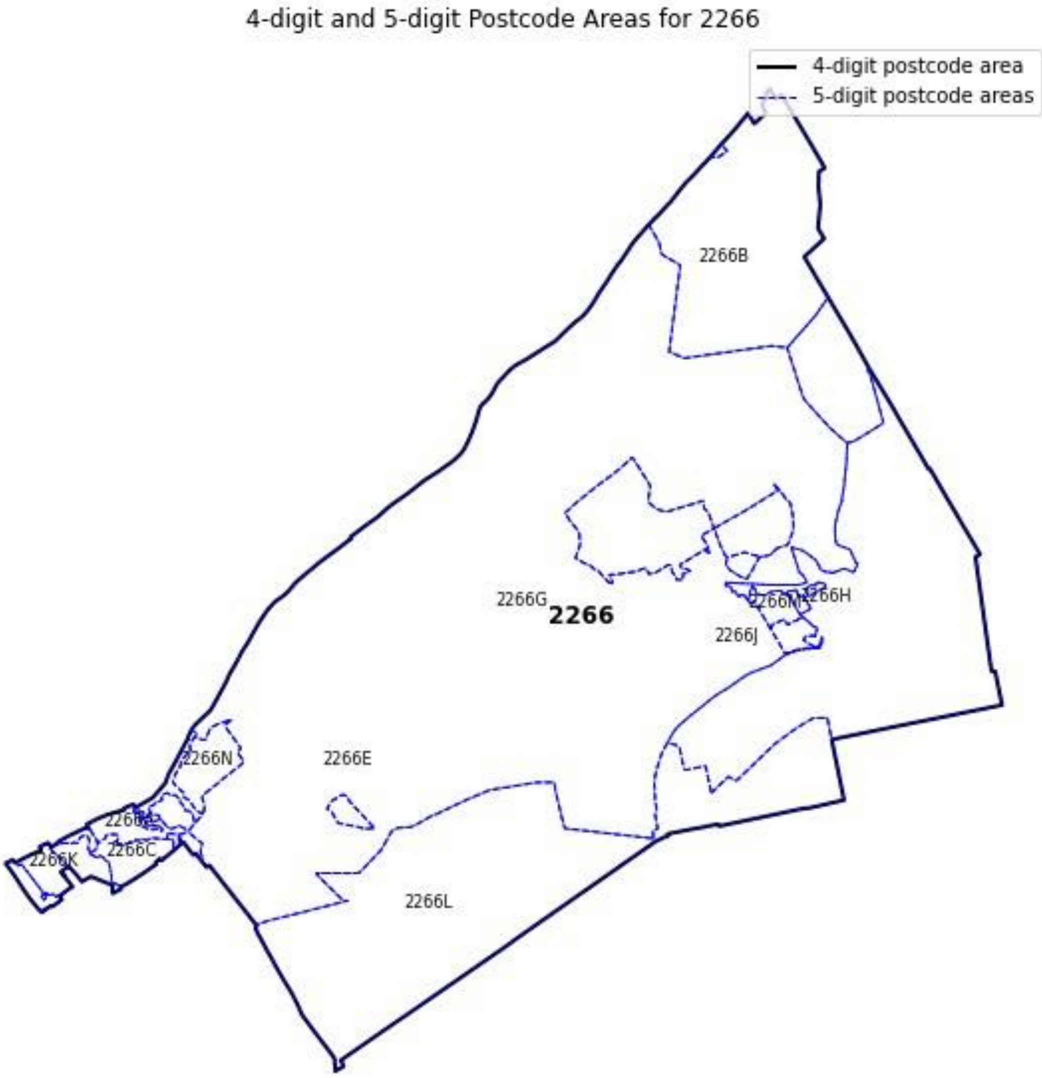

Figure 7: the 4-number postcode 2266 split up in its 5-number postcodes

Every 4-number postal code zone was broken down in their 5-number postal code zones. Every 5-number postal code zone has their own centroid, which was determined with the help of the Python package 'GeoPandas'. Every 5-number postal code zone also has data about its population. Combining the population and centroid for each 5-number postal code zone with the principle of finding the center of gravity results in a coordinate point which can be considered the demographic point of gravity, so the centerpoint of the population within that 4-number postal code zone.

Finally, objective three was achieved by writing code which stores all data for every city zone in a table and packages this smartly for use in other scripts.

4.3 Finding promising BRT corridors within the study area

All factors found for travel demand have been combined in order to find promising BRT corridors within the study area. According to section 2.5 a gravity model describes the relationship between a parameter such as population or jobs, a cost factor such as distance or travel time, and the travel demand.

Since the data does not include any information about the number of trips between zones, it was not possible to give an absolute indication of demand. Therefore the formula is made to give a BRT Score for a specified origin-destination pair, which indicates the relative suitability of a BRT corridor in relation to all origin-destination pairs within the study area.

The following formula calculates a BRT Score for every OD pair:

$$BRT\ Score_{ij} = a * \frac{P_i * J_j + P_j * J_i + \ P_i * P_j}{1{,}03 * 10^{-9} * \left(D_{ij} - 2{,}2 * 10^4\right)^2 + 1} * factor_{PT}$$

Where:

P = population

J = amount of jobs

D = great circle distance

a = a scaling factor

In this formula, a score for travel demand from home-work trips are described by multiplying the amount of jobs and inhabitants of both zones with each other. A score for travel demand for motives other then home-work, such as visiting friends and family, shopping or going to school, is described by multiplying the population of both zones with each other.

The great-circle distance between the zone pair determines the cost factor. The distance decay formula is of paraboloid form, with 22 km as top (

Figure 8). The distance decay function causes that distances shorter or beyond 22 km will result in a lower BRT Score. The constants in the formula are necessary to describe the paraboloid shape of the cost factor. One of the reason for choosing a paraboloid function was that for example distances under 5 km are more likely to be covered by bike. For example, a negative exponential function would always prefer the shortest distance, which is then not always suitable for a bus line. On top of that, distances over 30 km are assumed to likely be covered by train.

As discussed in the Theoretical Framework, the average length of BRT lines in Europe is 14,6 km. However, after consultation with the external supervisor, a distance of 22 km was chosen as ideal BRT line length for this research. The reason for this was the fact that within the study area, promising BRT lines connecting zones of different cities would likely cross rural areas and thus cover a longer distance, while the average length discussed in the Theoretical Framework is based on more urban BRT lines.

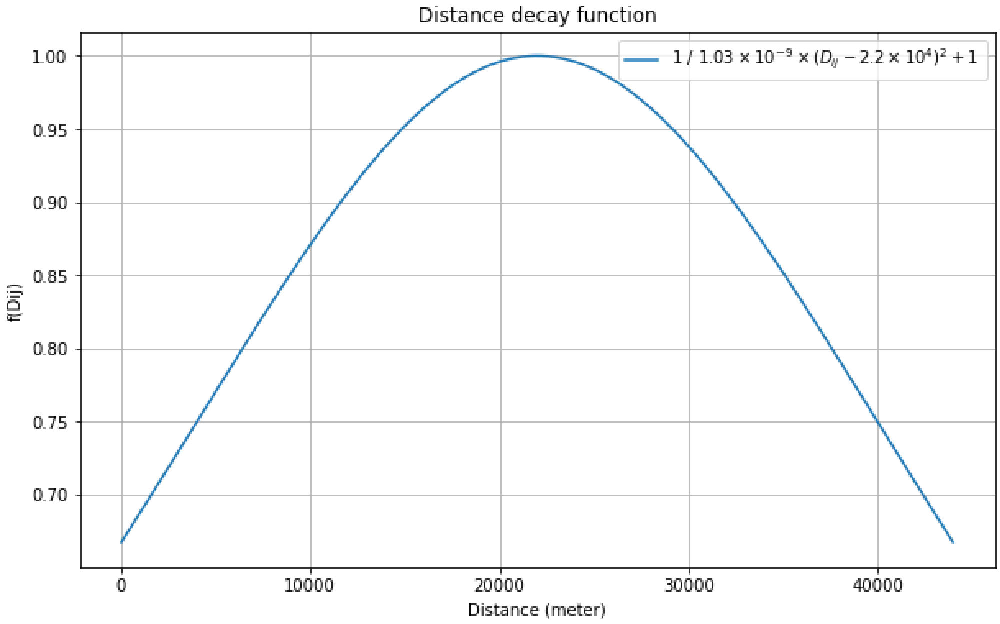

Figure 8: Shape of the distance decay factor

The scaling factor alfa is used to make the BRT Score more presentable. The general model of this thesis has a scaling factor of $1 * 10^{-7}$.

$factor_{PT}$ incorporates the level of existence of a good public transport connection between the two postal code zones.

$$factor_{PT} = \frac{T_{PT,ij}}{T_{car,ij}}$$

Where:

T_{PT} = public transport travel time

T_{car} = car travel time

The car travel time in this case is seen as the 'ideal' travel time. The equation leads to pairs with a relatively bad connection to receive a higher $factor_{PT}$ value and pairs with a relatively good connection receive a lower value. This is then multiplied with the first part of the formula, which leads to origin-destination pairs with equal results from part one to have a higher BRT Score if the relative public transport connection is bad, since part one is divided by a bigger number.

In the model, the public transport times were retrieved with the help of a Google Maps API. This way, the model can automatically fetch the travel times for every origin-destination pair. The car travel times are retrieved with the help of the Open Source Routing Machine API, which determines the travel times based on the maximum speed limit. The model automatically fetches the car travel time for every origin-destination pair.

4.4 Incorporating intermediate stops in the model

To form complete a BRT corridor, a method for automatically finding intermediate stops between origin and destination zones was developed. This method works for finding intermediate stops between any origin and destination within the study area. The method follows three steps:

1. Creating a buffer of a predetermined width, parallel to the straight line connecting the origin and destination
2. Finding every population center of each zone within this buffer to function as a stop location
3. Using Dijkstra's algorithm to find the shortest path connecting the origin, via the intermediate stops, to the destination

The width can be adjusted in the model. This is done because for example, a distance of 1km between the origin and destination a buffer width of more than 2km would not make much sense. By making this width a parameter which can be changed by the user, a more direct or indirect route of choice can be created.

To automatically find the shortest path between the origin, intermediate stops and destination, Dijkstra's algorithm was applied. At every stop, this algorithm calculates the distance to every unvisited stop. It then selects the path with the shortest distance, and moves to that stop. It then repeats the process until all stops are visited. It makes sure to start at the origin and always end at the destination.

The model was also made to calculate the most efficient combination of intermediate stops. In this case, efficiency is defined as the balance between the BRT Score and total travel time. It achieves this by automatically determining all possible intermediate stop combinations. For example, if you have combination A-B-C-D, it will generate the combinations A-B-D, A-C-D, A-B-C-D (given that A and D function as origin and destination and therefore always have to be included). Then, for every combination, the model calculates the total car travel time using the Google Maps API, to give an estimation of how long a BRT line would take to visit all stops. Then, the model calculates the BRT Score for every combination by adding all separate OD pairs which have their own BRT Score. Taking the example of A-B-C-D, the BRT Score calculator already has a list of BRT Scores for the pairs A-B, A-C, A-D, B-C, B-D and C-D. So for the combination A-C-D, only the BRT Scores of the pairs A-C, A-D and C-D are summed. Then, to calculate the efficiency of each combination, both the BRT Score and car travel time are normalized, by assigning 0 to the lowest value of these, and assigning 1 to the highest value. All values in between thus receive a number between 0 and 1. Then, a weight is multiplied with these normalized values. The weight can be changed depending on whether travel time or the BRT Score has higher priority. The final number is considered the efficiency for each combination.

4.5 Finding promising BRT corridors to and from Schiphol

In the case of finding promising BRT corridors to and from Schiphol, a variation of the general model for calculating BRT Scores was applied. First of all, a more exact location of Schiphol was determined, since in the general model only the population centers of postal code zones were defined. It was chosen to select Schiphol Plaza as the destination point for every origin-destination pair. Besides that, for retrieving both the car and public transport travel times between the origin-destination pairs the Google Maps API was used, as it was expected that using the same platform for both instances would give more accurate results. Previously the OSRM API was used to retrieve the car travel times, since the Google Maps API was limited to a certain amount of requests, which were reserved for fetching the public transport travel times. Using the Google Maps API was deemed possible in the Schiphol case because of the limited amount of origin-destination pairs.

On top of that, the formula for estimating the BRT Score for every origin-destination pair was slightly adjusted for this case. The change includes the removal of the number of jobs as factor within the formula. It was assumed that most trips to and from Schiphol would originate from and finish at home. Therefore population, great-circle distance and the difference between car and public transport travel time were the chosen factors for this case.

The used formula is the following, where i represents Schiphol and j a zone within the study area:

$$BRT\ Score_{ij} = a * \frac{P_i}{1{,}03 * 10^{-9} * \left(D_{ij} - 2{,}2 * 10^4\right)^2 + 1} * factor_{PT}$$

Where:

P = population

D = great circle distance

s = a scaling factor

$factor_{PT}$ stays the same:

$$factor_{PT} = \frac{T_{PT,ij}}{T_{car,ij}}$$

Where:

T_{PT} = public transport travel time

T_{car} = car travel time

4.6 Verification of the model

The aim of model verification is to make sure that the model is correctly implemented, without any errors and is consistent for any input within its constraints. The verification was performed in three steps:

1. Input data verification
2. Modular code testing
3. Code testing with different data sets
4. Sensitivity analysis

The input data verification was performed both by applying data analysis on the input datasets (car and public transport travel time) and by manual inspection (geometry data, population data, job data, distance between city zones). This way, any irregularities or outliers which could influence the outcome of the model could be detected. By importing the datasets into Excel, simple data analysis could be performed by using the respective tool. With that, the main characteristics of the dataset, like mean, median, minimum and maximum were revealed. Besides, producing a histogram of the datasets helped visualize the data and detect outliers. The calculation of great-circle distance between population centers of the city zones was manually verified by randomly comparing an amount of calculated values with the values given by the distance calculation tool in Google Maps. The population and job data was manually inspected by sorting on maximum and minimum values and determining if these values seemed realistic.

Modular code testing was performed throughout the whole process of building the model. For every major step in the model, a new script was opened. This way, errors could be more easily identified as they would relate to a certain step in the model. Besides solving errors preventing the code to continue running, intermediate output data was verified in order to check whether the model produced any unexpected numbers. The intermediate output data was verified by randomly selecting an input value and manually computing the outcome, and comparing this with the model outcome. This was done in model parts where formulas were applied. In case of the model part where car and public transport travel times were fetched by the API, the results were verified by randomly selecting origins and destinations and comparing these API results with the current travel times given by Google Maps. For model parts where data was merged into one table, it was randomly checked whether the values of a specific row where assigned to the right origin-destination pair, and whether the values were assigned to the right column.

The third step of the verification was to test the code with different datasets, to ensure that the model was consistent for use in other study areas within The Netherlands. Different Geopackages containing different geospatial data were imported to find out whether the model plotted the data for every Geopackage correctly. By inspecting the output figure, which contain borders of the city zones and their respective population center and centroid plotted on an Openstreetmap background, any inconsistencies could be detected. Besides that, a case study for Schiphol Airport was developed which gave insights of whether the model was applicable to these specific cases. It was verified if the model would not produce errors in a specific case, and if the output data was consistent. During the execution of the case, the API was run again to gather car and public transport travel time, showing if the API behaves as expected for a different dataset.

A sensitivity analysis was performed to verify whether the formula for calculating the BRT Score is applied correctly. A Python script was written to automatically perform the sensitivity analysis. After the base values are defined, the model calculates the BRT Score for every parameter separately, while varying this parameter between 50% and 150% of its base value. Meanwhile, the other parameters stay fixed. The model then produces a figure showing the percentage of change of each parameter versus the percentage of change of the BRT score. This figure showed the relationship between each parameter and the BRT Score. The relationship in the figure was compared with the expected relationship from the formula calculating the BRT Score (linear, exponential, etcetera). Also, the results could give an indication whether the change in parameters of different magnitudes resulted in a correct change in BRT Score.

4.7 Validation of the model

The aim of model validation is to make sure that the model accurately reflects the real world situation, such that the model should fulfil its purpose as good as possible. The validation was performed in three steps:

1. Sensitivity analysis
2. Expert review
3. Comparing the outcome of the model with proposed BRT routes by other parties
4. Documentation of the model

The results of the sensitivity analysis could also be interpreted in another way, in order to validate the model. The robustness of the model was validated this way, as it shows whether the model is reliable under different conditions. The sensitivity analysis also shows if the model reacts to unseen parameter values as expected in the real world situation.

An expert review was conducted to ensure that the model is conceptually correct. The supervisors of this thesis are considered expert in the field of public transportation. In a meeting with me and the experts, a discussion about the formula and concept of the model in general was sparked. Besides that, intermediate model results were discussed with one of my external supervisors.

The promising BRT connections proposed by the model were compared with earlier proposed BRT connections by other parties within The Netherlands.

The model was documented as clearly as possible, in order to be used by other parties in different scenarios. This ensures that the logic behind the model is understandable by anyone, adding to its transparency.

5 Results

In this chapter, the results of the research will be presented, organized per research question.

5.1 What factors determine BRT travel demand between zones?

From the information collected in the Theoretical Framework, it was decided to use the following factors in the model:

1. Number of residents
2. Number of jobs
3. Distance
4. Difference between car travel time and current public transport time

Factor 1 and 2 represent the categories Demographics and Economics as seen in Table 1. While the distance factor is not specified in Table 1, it aims to capture land use characteristics. Factor 4 aims to capture demand based on available transport options. This means that factors regarding ticket pricing and service quality are not included in the model.

5.2 What do the zones look like which make up origins and destinations?

It was found that the database by CBS (Centraal Bureau voor de Statistiek) provided data that meets the following criteria:

1. The size of the city zones should be the size of a city neighbourhood
2. Population data and geometry data is available for each city zone
3. City zones and their data must be available for the whole of The Netherlands

The data was downloaded in Geopackage format, which captures the geometry data of the city zones. The database provided data on different scale levels.

However, data about jobs in each neighbourhood was not available from CBS. This data was purchased from organisation LISA, which captures data about jobs within The Netherlands. The smallest scale on which this data was available was 4-number postal code level. For that reason 4-number postal code zones where chosen as the scale level for this research.

Figure 9 shows the 4-number postal code zones within the study area with their respective population center. The centroid for each zone is also displayed to visualize the difference between the population center and the centroid.

The study area in the figure includes a range of cities within the Randstad, as well as Schiphol. The scope of this particular study area was severely limited by further steps in the research.

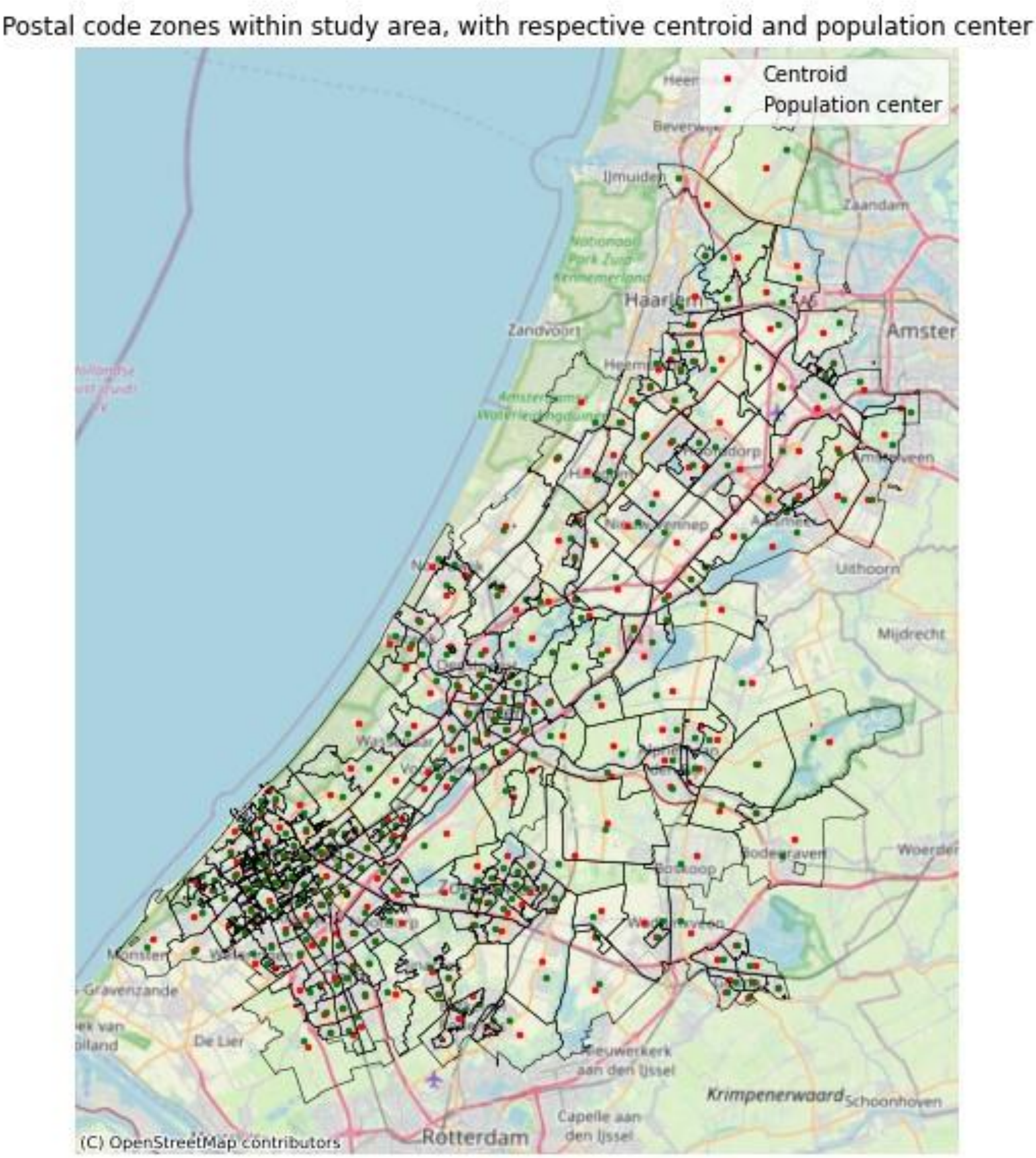

Figure 9: Postal code zones within study area with their centroid and population center

The distance between the centroid and population center of each zone is not very large, but reveals that the population center gives a better representation of where most people live, looking at where towns are situated on the map. Also, it becomes apparent that cities like Leiden and The Hague consist of many postal code zones whereas rural areas are defined by much bigger zones.

5.3 What are promising BRT corridors within the study area?

The model calculates the BRT Score for each postal zone pair, the top ten of which can be seen in Figure 10 and in Table 4.

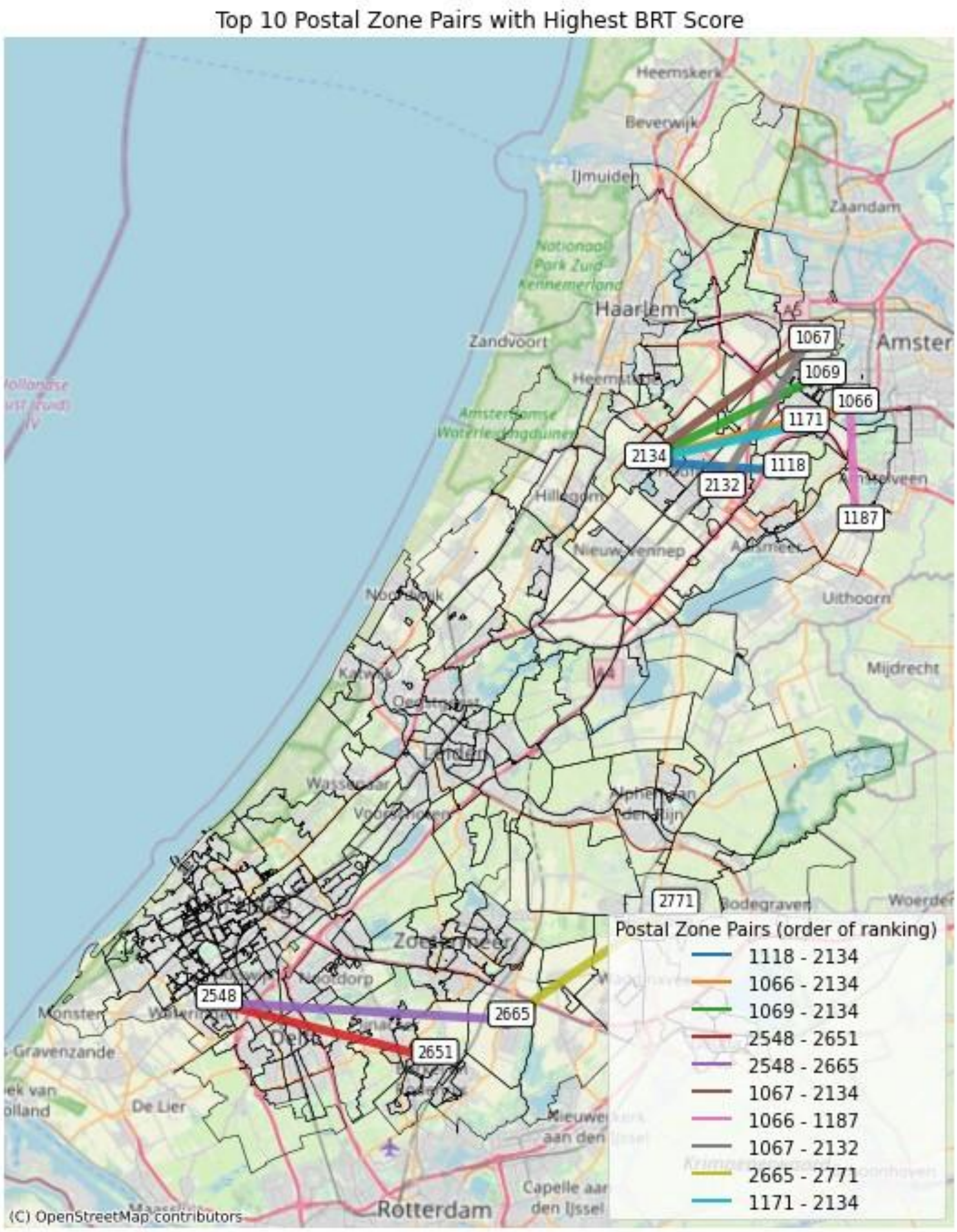

Figure 10: Top 10 postal zone pairs with highest BRT Score

Table 4: Top 10 zone pairs with highest BRT Score, with their corresponding municipality name

Rank	Origin (postal code + municipality)	Destination (postal code + municipality)	BRT Score	Great circle distance (m)
1	1118 (Haarlemmermeer)	2134 (Haarlemmermeer)	29505	6806
2	1066 (Amsterdam)	2134 (Haarlemmermeer)	28925	12125
3	1069 (Amsterdam)	2134 (Haarlemmermeer)	25390	10970
4	2548 (Den Haag)	2651 (Lansingerland)	22332	13217
5	2548 (Den Haag)	2665 (Lansingerland)	22219	17090
6	1067 (Amsterdam)	2134 (Haarlemmermeer)	21086	12564
7	1066 (Amsterdam)	1187 (Amstelveen)	19452	7261
8	1067 (Amsterdam)	2132 (Haarlemmermeer)	18950	11109
9	2665 (Lansingerland)	2771 (Alphen ad Rijn)	18792	10855
10	1171 (Haarlemmermeer)	2134 (Haarlemmermeer)	18658	9715

The results show a concentration of promising BRT corridors in the area Haarlemmermeer and Amsterdam. Three promising BRT connections in the province of South-Holland reach the top ten. It is interesting to see that multiple zones connect to more then one other zone within the top then.

To display the results in an interactive way, a webapp was developed which allows selecting a postal zone and seeing a predetermined amount of top corridors (Figure 11).

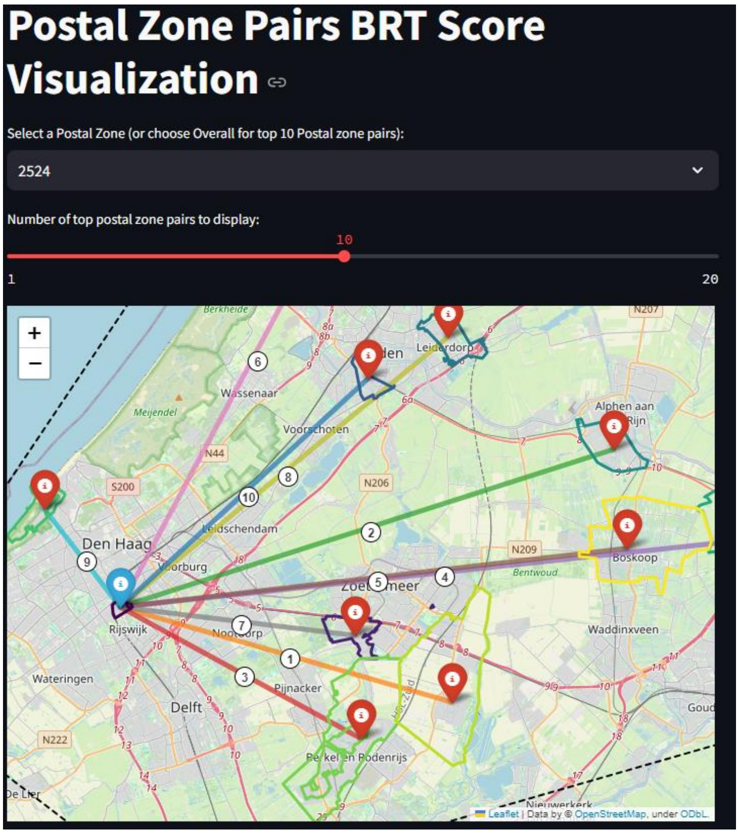

Figure 11: Screenshot of the webapp displaying promising BRT corridors for a chosen postal code zone, in this case 2524

5.4 In what way can intermediate stops be included in the model?

When the model is run for a specific origin-destination pair, for example 2134-1187, it will generate the shortest route between the origin, all intermediate zones and the destination, as displayed in Figure 12.

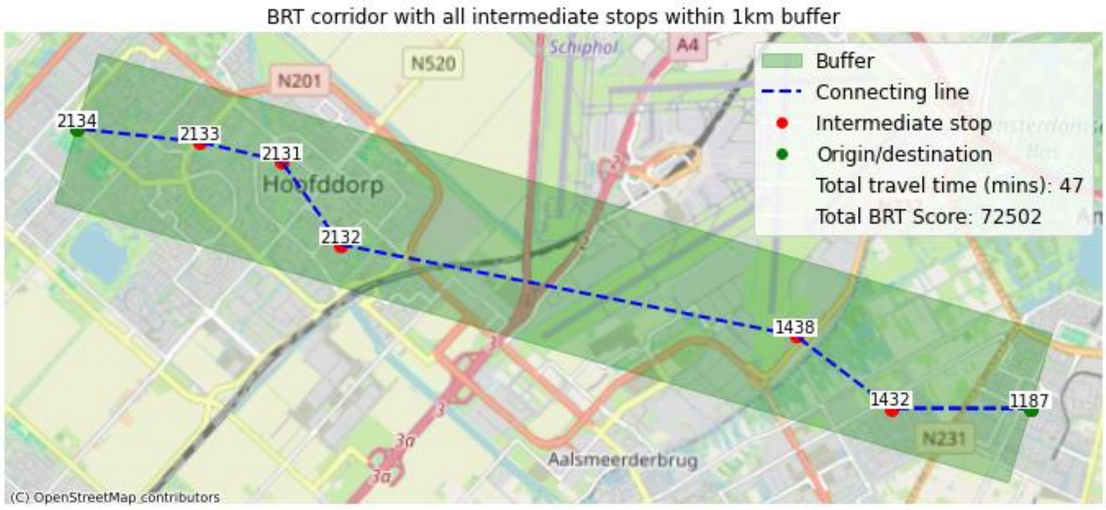

Figure 12: Shortest path of promising BRT corridor between 2134 and 1187 with intermediate stops and BRT Score with and without intermediate stops

It can be seen that the connecting route indeed takes the shortest path between the intermediate stops, but looking at the background map it does not look like a realistic route. The connecting lines are completely straight and ignore existing infrastructure.

While Figure 12 shows the route with all intermediate zones, this is not the most efficient route according to the model. The most efficient route, with equal weights for travel time and BRT Score, skips intermediate zones 2131 and 2132. This route saves 14 minutes of travel time, but with the compromise of having a lower BRT Score.

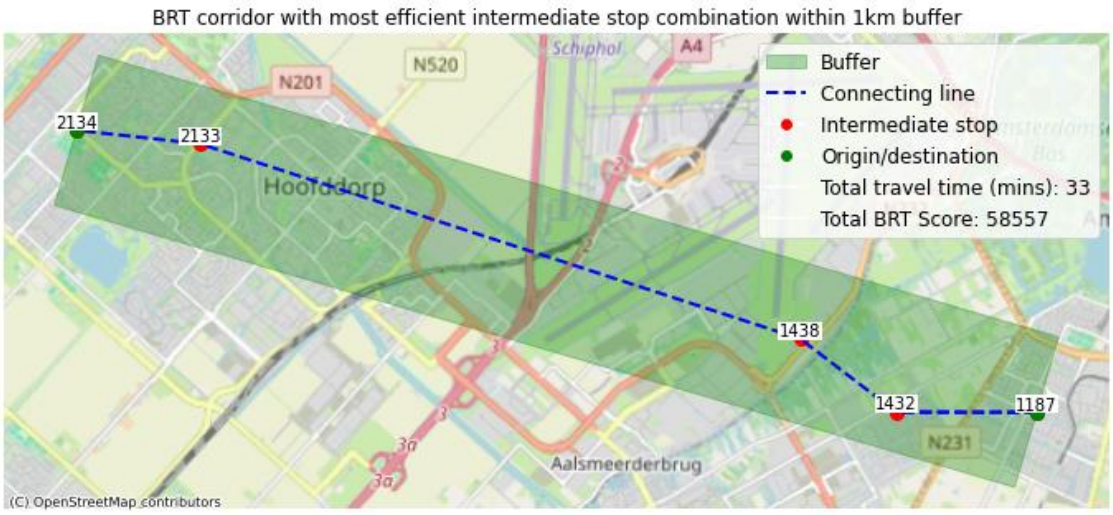

Figure 13: Most efficient BRT corridor according to the model

5.5 What are promising BRT corridors to and from Schiphol?

The model calculates the BRT Score between Schiphol and each postal zone pair, the top ten of which can be seen in Figure 14 and in Table 4.

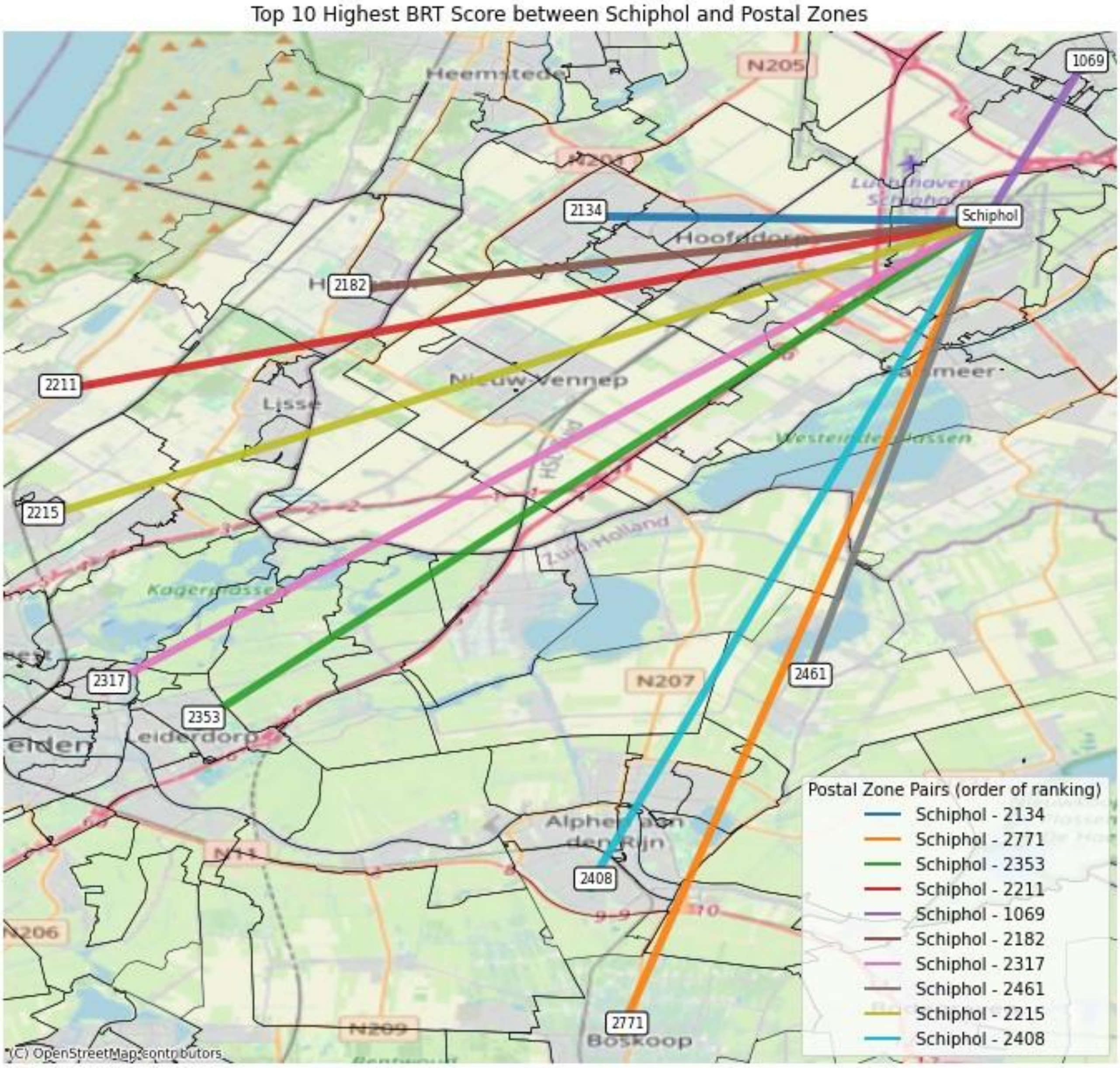

Figure 14: Top 10 BRT corridors between Schiphol and all postal code zones within the study area

Table 5: Top 10 zone pairs with highest BRT Score, with their corresponding municipality name

Rank	Origin	Destination (postal code + municipality)	BRT Score	Great circle distance (m)
1	Schiphol	2134 (Haarlemmermeer)	3266	7946
2	Schiphol	2771 (Alphen ad Rijn)	2565	26865
3	Schiphol	2353 (Leiderdorp)	2355	22325
4	Schiphol	2211 (Noordwijk)	2167	19077
5	Schiphol	1069 (Amsterdam)	1991	5332
6	Schiphol	2182 (Hillegom)	1952	12784
7	Schiphol	2317 (Leiden)	1868	22898
8	Schiphol	2461 (Nieuwkoop)	1829	15135
9	Schiphol	2215 (Teylingen)	1693	20925
10	Schiphol	2408 (Alphen ad Rijn)	1689	22634

What stands out is that the top ten is quite diverse, the promising BRT corridors from Schiphol reach in all directions within the study area. Also, it is notable that around 7 corridors within the top ten approximately have the same distance between Schiphol and the destination. The destinations within the top ten not only include bigger cities like Leiden or Alphen ad Rijn, but also smaller villages like Boskoop.

5.6 Verification

1. Input data verification

Population data and geometry data about each postal code was taken from CBS. By manual inspection, it was found that for some postal codes the values for population was equal to -99997. Due to privacy reasons, CBS is obliged to hide the exact population number if this number is considered ‘too small’. An exact value is not given to this limit. Further manual inspection of the geometry and population data showed no irregularities. The data about the amount of jobs per postal code also showed no irregularities. The great-circle distances between the population centers of the city zones was found to be correctly calculated by the model as comparison with the Google maps distance calculation tool showed consistent overlap.

The car and public transport travel times used as input for the model calculating the BRT Score were initially manually verified. The public transport travel times showed inconsistent results. Therefore further data analysis in Excel was performed. Histograms for both car and public transport travel times (Figure 15 and Figure 16) were created.

The car travel time data shows a more consistent histogram shape without a notable amount of outliers.

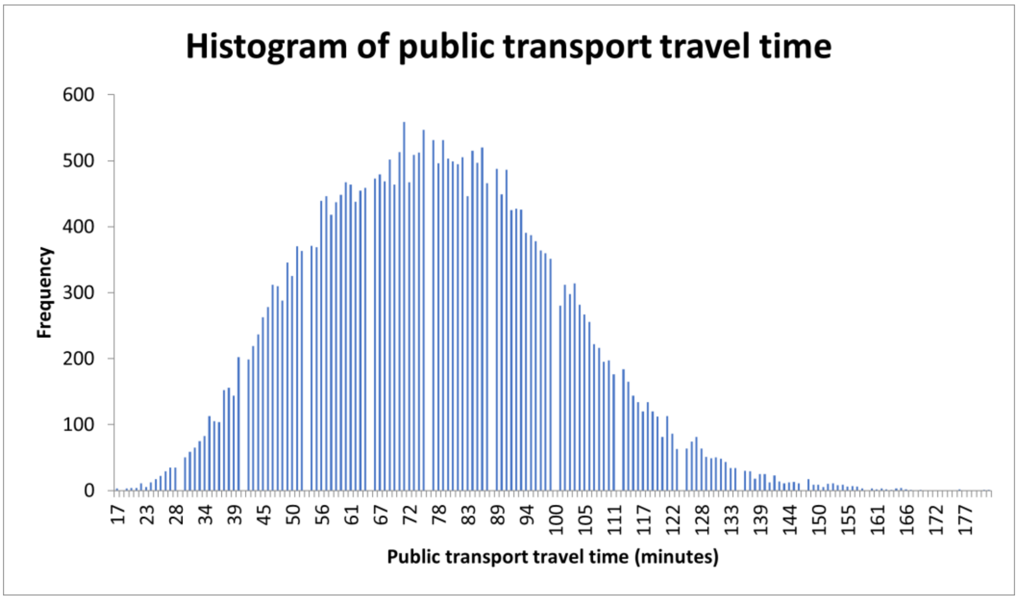

Figure 15: Histogram of public transport travel time between zones

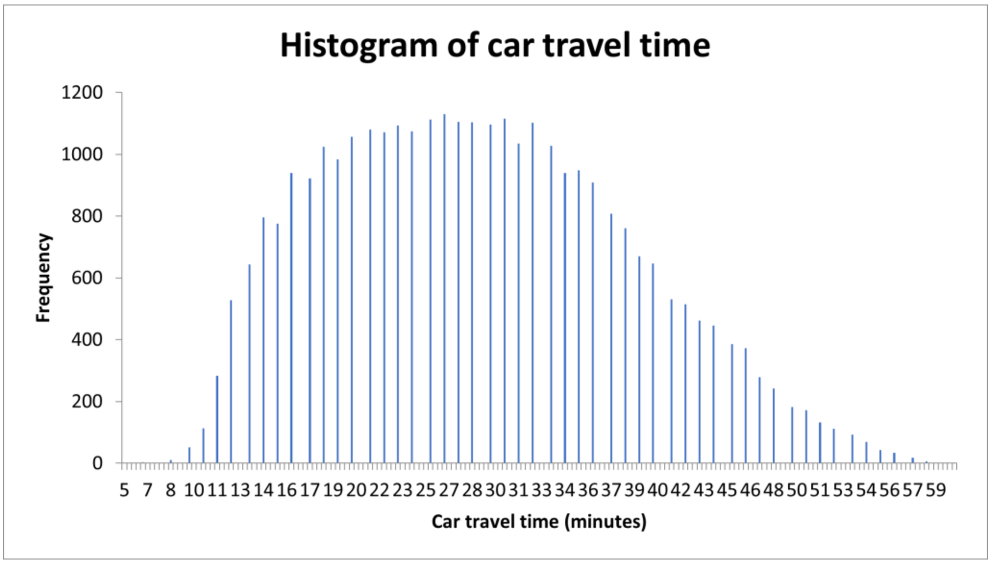

Figure 16: Histogram of car travel time between zones

2. Modular code testing

The model consists of 9 parts which all perform a separate step towards the plotting of results. Whenever mathematical formulas were applied within the model, the results were found to be consistently correct. Intermediate results involving point geometry data or coordinates were checked carefully after running into issues with a wrong coordinate system, but after consistently converting point geometry data and coordinates to the right system the model generated expected results. The car and public transport travel time data was manually checked with the use of Google Maps, and showed some inconsistencies. However, most randomly chosen travel times did closely correspond to the Google Maps values, but mostly did not overlap exactly.

3. Code testing with different data sets

The model was tested with different Geopackages containing different geospatial data for different study areas. The model was found to correctly convert these Geopackages to a plot, showing the postal code zone borders, centroids and population center for each postal code zone. The case study with Schiphol Airport showed that the model behaves as expected with other datasets. It did not give any errors or unexpected results.

4. Sensitivity analysis

The following base values for every parameter were used:

- population_origin: 10000
- jobs_destination: 10000
- population_destination: 10000
- jobs_origin: 10000
- distance: 20000
- percent_difference: 250

The values were based on input values from the top 10 BRT Scores. The values are approximated for easier visualisation.

The sensitivity analysis Figure 17 shows that every parameter has a specific relation with the model outcome (the BRT Score).

For ‘population_origin’, ‘jobs_destination’, ‘population_destination’, ‘jobs_origin’ and ‘percent_difference’, a linear relationship between the parameter and the BRT Score can be seen. A paraboloid shape describing the relation between the ‘distance’ parameter and the BRT Score is visible. Besides that, it can be seen on the y-axes that a change in population causes double the change in BRT Score compared to a change in jobs.

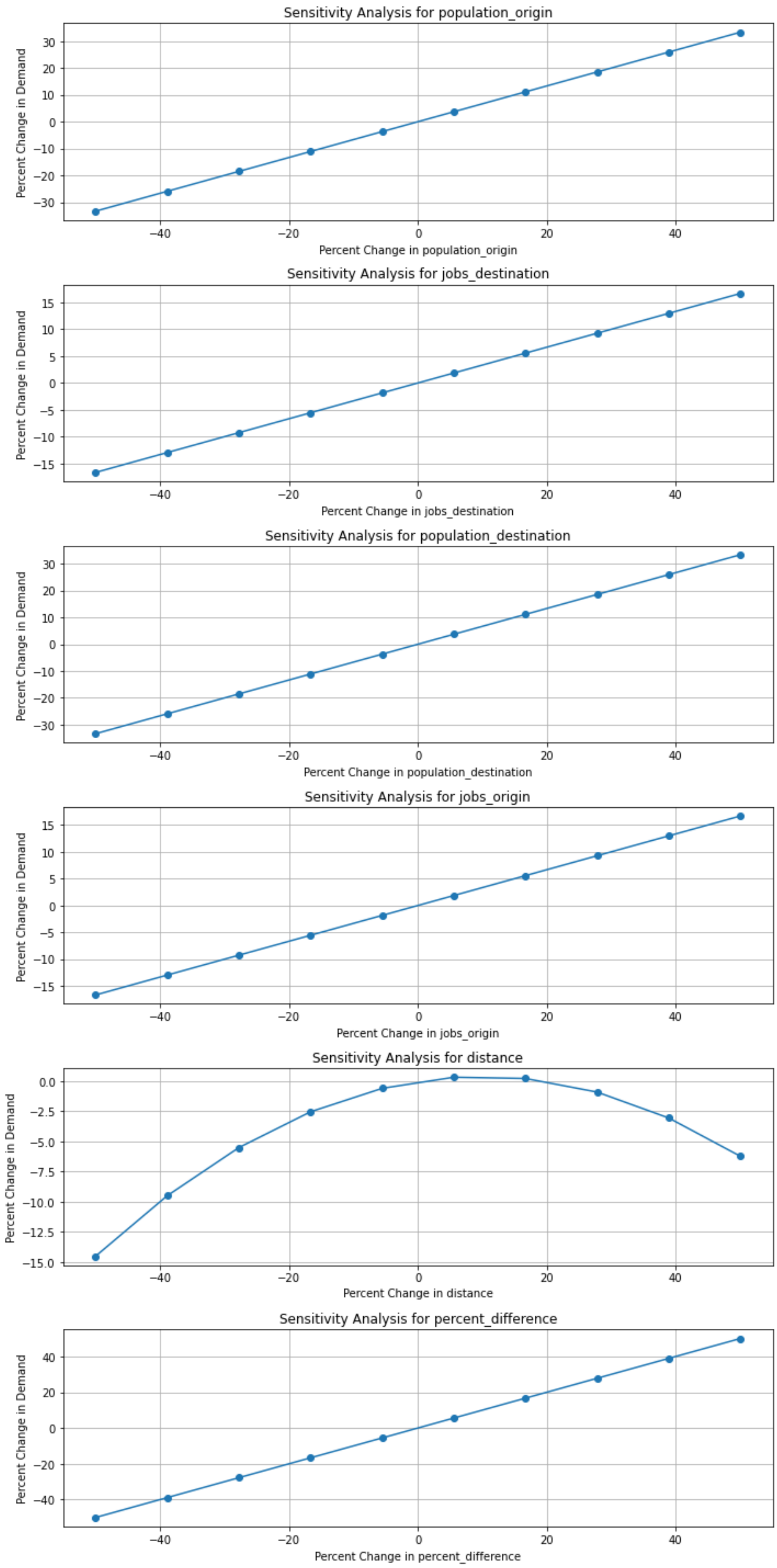

Figure 17: Graphs representing the results of the sensitivity analysis for each parameter in respect with the BRT Score

5.7 Validation

1. Sensitivity analysis

The results of the sensitivity analysis show no outliers or strange relationships. Unseen parameter values seem to fall within a trendline. Besides that, an increase in distance smaller or larger then 22000 causes a lower BRT Score.

2. Expert review

The meeting with me and the supervisors resulted in a few remarks:

- A BRT Score does not imply demand or ridership. After the meeting it was more clearly stated in the report that the BRT Score only represents a suitability measure for BRT lines, and not actual demand.
- The top of the parabola for parameter 'distance' may need to be moved to a further distance, as BRT within The Netherlands may have a longer average length then 14,6 km (the distance discussed in the Theoretical Framework). A distance between 20 and 25 km was proposed, after which 22 km was chosen. It was noted that for shorter distances, it was more likely that people would choose the bike as mode of tansport, whereas a much longer distance then 25 km people would probably choose the train.
- Population center is a better representation of a postal code zone's centerpoint instead of the centroid. This remark was followed up on early in the research, by using the 5-numbered postal codes to find the population center.
- In case of Schiphol Airport, the amount of travellers must be taken into account next to the amount of jobs. However, this was eventually not done in this research, as suitable data was not found. Instead, the gravity model based solely on population, great circle distance and car and public transport travel time was used.

Apart from these remarks, the model was found to represent the real world situation to a certain extent and achieve the model objectives as good as possible.

3. Comparing the outcome of the model with proposed BRT routes by other parties

De Wit (2024) found a few promising BRT corridors resulting from his model, seen in Figure 18. This thesis is a continuation of the work by de Wit, so comparing the results seems logical. However, the promising BRT corridors found by de Wit fall outside the study area of this thesis.

Figure 18: Most promising BRT corridors found by de Wit (2024)

A working group on BRT (Decentrale OV Autoriteiten, 2022) collected plans for BRT in The Netherlands. The red lines in Figure 19 represent current plans for BRT, the blue lines represent the current railway network. The corridor Den Haag-Naaldwijk-Zoetermeer shows up both in this collection of plans as well as in the results of this thesis. Also, a cluster of plans around Schiphol is visible in both this thesis and the collection of plans, one of them being the corridor between Schiphol and Hoofddorp and between Schiphol and Alphen ad Rijn.

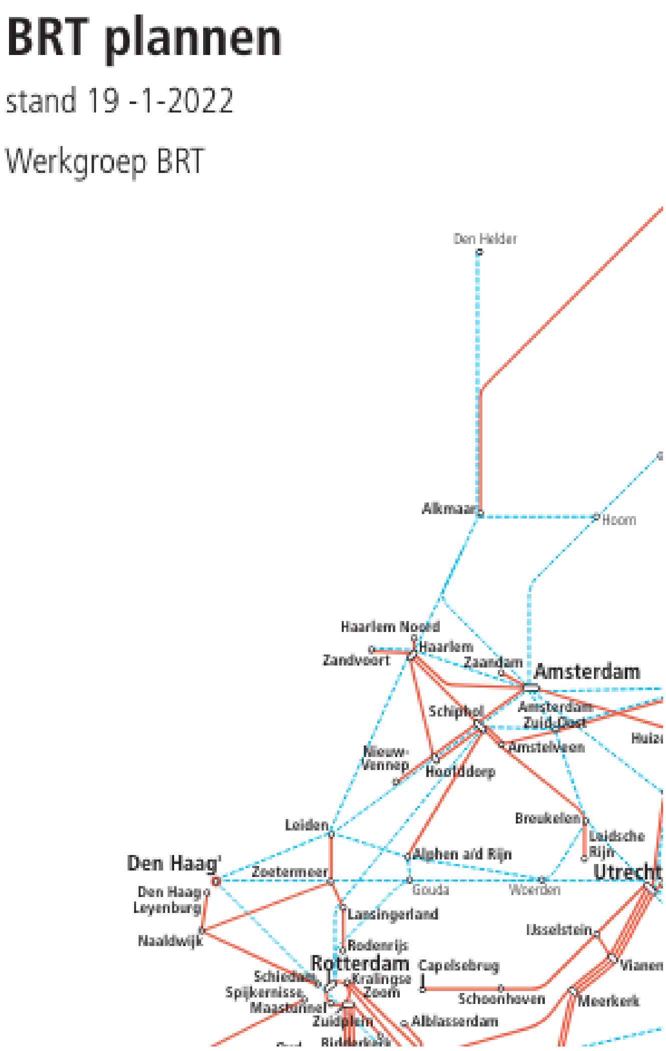

Figure 19: BRT plans for The Netherlands, represented by the red lines

4. Documentation of the model

All model parts, together with a ReadMe which functions as guide, were uploaded to code sharing platform GitLab (https://gitlab.com/luuk9061221/BRT). All Python packages used are listed together with their version, which helps assure that the model can be run in the future too.

6 Discussion

In this chapter, the interpretation of the results are discussed and limitations of the research are acknowledged, organized per research question.

6.1 What factors determine BRT travel demand between zones?

Although the most suitable factors describing BRT travel demand between city zones have been chosen, actual demand in terms of amount of trips cannot be determined since this requires the construction of an origin-destination matrix. Such matrix shows the distribution of trips between a set of origins and destinations. Since data about trips between the selected zones is not available for this research, instead of the number of trips a BRT Score indicates the suitability of a BRT corridor.

The chosen factors used in the formula for the BRT Score, and the formula itself, are not perfect, and the following constraints apply:

1. The BRT Score says nothing about actual demand, but rather provides a suitability score. This score can only be used to compare all OD pairs within a specific study area.
2. Combining multiple factors, like number of jobs, population and travel time can give an unrepresentable BRT Score, since the different factors all have a different scaling. Just like comparing apples with pears, the model compares population and travel time, which are not the same value. The different factors are expressed in different values, and it may not be reliable to compare these. However, because this approach is similar for the whole study area, the relative comparison can be considered fair.
3. Travel demand between zones based off population does not only indicate trips between homes. Shopping trips or school trips made with public transport are incorporated in this number as well. Assuming that more shopping trips are made between zones with a large population number could be a correct assumption, but this cannot be proven, since shopping locations are not incorporated in the model.
4. Although the job data seems to be sufficiently up-to-date (2022), it ignores the number of workers who work from home for a certain amount of days per week, which leads to the model overestimating the demand for travel based on the job data. On top of that, for some job sectors, the percentage of people working from home is likely higher than for other sectors.
5. Major trip generators such as hospitals, universities, stadiums and tourist attractions are hard to incorporate in a general model. Since these locations can be considered an exception when it comes to travel demand, it is hard to generalize them in one model. It was tried to incorporate a list of hospitals and universities in the dataset, but it was found that not every hospital or university has the same size and thus not the same travel demand. However, the model does incorporate these major trip generations in an indirect way: the total number of jobs also includes jobs in that particular hospital or university. This way the issue of generalizing all

hospitals and universities to one number is solved automatically, since major hospitals or universities have a higher number of jobs, and smaller hospitals or universities have less. On the other hand, the travel demand is still underestimated this way, as in reality visitors to hospitals create travel demand which the model does not incorporate. The same counts for universities, the travel demand for students going to class is not incorporated in the model. Also, if a stadium hosts a big event, the travel demand for this is not incorporated in the model.

6. Seasonality is not incorporated in the model. Travel demand is never the same; in the summer holiday, travel patterns are different then in a regular winter work week. In the weekends, travel patterns are different then during weekdays. During rush hour, travel patterns are different then outside rush hour. Even a Tuesday rush hour is different then a Wednesday rush hour.
7. The number of jobs makes up a large share of estimated travel demand in the model, which would mean that the travel demand is severely overestimated in the weekends, as a large share of employees is home for the weekend. Also, if the model were to be adapted for the weekend, the amount of jobs would be dropped by a large share. This way, the travel demand seems to be relatively low, but demand may still be high for people that make day trips or visit family in the weekends.
8. Currently, OD pairs are given a higher BRT Score when the existing public transport travel time is relatively low compared to the car travel time. The question also arises whether taking the car travel time as ideal travel time is realistic. It could be the case that people accept a certain time loss when using public transport, when the price is acceptable. However, since the assumptions about ideal travel time apply equally to all OD pairs, it can be considered a fair comparison.
9. The 22 km chosen as ideal length for a BRT line may not have been the best choice for the gravity model. In the end, the gravity model should be based on average trip length, instead of BRT line length. Since the research was almost concluded after this point of discussion was brought up, the value was not changed. On the other hand, it is assumed that a distance of 22 km is not far from actual average trip length. One reason for this is that for distances below 5 km, people tend to cycle to their destination. On top of that, for distances over 30 km, it was assumed that people are likely to use the train.
10. There is a difference between BRT lines within urban areas and lines between urban areas. Promising BRT lines which run for the most part within urban areas may have a shorter distance to be efficient, while promising BRT lines between smaller cities which cross rural areas may have a longer effective distance. Regarding the most ideal length of a BRT line, this can be considered a case to case question, therefore the assumed average length of 22 km may not be realistic for each case.

6.2 What do the zones look like which make up origins and destinations?

First of all, the zones functioning as origins and destinations turned out to be of a larger area than planned in the research proposal. 'Neighbourhood' level was described in the research proposal, which is considered a smaller zone size. However, 4-number postal code zones were the minimum size possible due to the available data. The 4-number postal code zones can be considered detailed enough for this research. This leads from the fact that cities are sufficiently broken down on this scale level, knowing that the objective of this research was to find promising BRT corridors between city zones.

However, the 4-number postal code zoning system is made for delivering mail, and is not made for representing demand for travel. While the size of the zones fits the research, the type of zone is not the best fit for this research as it ignores characteristics for travel demand. For example, the zones do not consider land use types. Using zones which are determined by whether an area includes residential or commercial buildings can be considered more useful as it may better describe travel demand between them.

According to the research proposal, the Randstad would function as the main study area. In practice, the study area had to be limited significantly. Except for (the major part of) Amsterdam and Rotterdam, major cities within the Randstad are included in the study area. The reason for this limit is primarily the limit of free use for the Google Maps API, which automatically determines the public transport travel time between every postal code pair. The free limit of the Google Maps API is 40.000 requests, which comes down to the number of possible pairs of around 290 postal codes. On the other hand, this limited study area also decreases model run time.

The model was built in such a way that any study area within the Netherlands can be used, with the criterion that the user of the model is willing to pay for the Google Maps API if the limit of 40.000 requests is exceeded and is willing to pay for the job data provided by LISA.

For every city zone, a coordinate point was specified in order to calculate the great circle distance, public transport travel time and car travel time between two city zones. This method however generalizes the entire city zone to one specific point, which leads to losing individual characteristics for a city zone. A way to cope with that to an extent was to locate a coordinate point which is the centerpoint of the population, also known as the demographic point of gravity. This reduces the chance of selecting a coordinate point outside of urban areas, in which the travel demand is close to zero.

However, estimating the public transport travel time between the calculated population centers may not be the best approach in every case. For a certain city, it may be logical to select its biggest train station as centerpoint, but instead, population is the only factor for determining this point. This may lead to an overestimation of public transport travel time between city zones. In other words, if a major public transport stop would be taken as centerpoint for each city zone, the public transport travel time would turn out lower as walking time is greatly reduced.

Besides, taking population as only factor for determining the coordinate points ignores the location of jobs in a city zone. For example, demand for travel may be high to a certain city zone due to the presence of an industrial zone, but the coordinate point is placed on a nearby town as this is the only population center in that city zone. This leads to an unrealistic representation of travel time to this industrial zone.

6.3 What are promising BRT corridors within the study area?

The results show promising BRT corridors which do not seem unrealistic considering the results of the validation step. The cluster of corridors around Schiphol can be explained by the high population of zones around Schiphol and the big number of jobs within Schiphol.

However, it should be remembered that the model only considers the characteristics of individual postal code zones and distance and travel time between two. This explains why some BRT corridors run between smaller villages, which on first sight would not make sense. But if by chance these zones contain a large population number or number of jobs, the corridor still ends up high in the list of promising corridors. Because this research aims to find promising BRT connections between city zones, it can be doubted whether corridors found between smaller villages are considered valid. The model namely ignores implementation in the complete public transport network. If a promising BRT connection between zones of larger cities is found, the impact may be relatively big since this corridor now connects two major local public transport networks. While when two smaller villages are connected, the impact may be smaller since the existing public transport network of these villages is small.

6.4 In what way can intermediate stops be included in the model?

One of the research objectives was to connect multiple stops to form a more complete BRT line. This is automated in a Python model, with the use of Dijkstra's algorithm to find the shortest path between stops. While the algorithm finds the shortest path between every pair of stops, it does not guarantee that the overall route is the shortest. The total route is only a collection of shortest paths between stops. This could be solved by implementing a more sophisticated algorithm, which still applies Dijkstra's algorithm but then compares every possible route to find the overall shortest path. However, this requires a lot more processing time.

It can be said that the inclusion of intermediate stops fulfils the role of increasing connectivity; which suits the overall purpose of this research. The more stops a line has, the more travel options are available. Only an origin and destination with for example 40 km in between, likely does not reach its ultimate potential. The model shows that a route with intermediate stops has a higher BRT Score compared to a route without intermediate stops. However, specific numbers about ridership are not calculated in the model, so it is hard to estimate whether a found BRT line would be under- or over capacity with the amount of intermediate stops found. If a found BRT line would be over capacity, intermediate stops would have to be skipped or the frequency should go up. If a BRT line is under capacity, more intermediate stops can be added. Decreasing frequency in this case is not favourable since BRT should include frequent service.

The model now only finds intermediate stops within a buffer between the origin and destination, forming a relatively straight line between the two. However, in the real world, it can be seen that bus lines are usually not designed in a straight line, but curve through cities and rural areas. On the other hand, buses are considered more comfortable if they make less turns. Maybe designing bus lines in a straight line is a good method from that perspective.

The model now totally ignores existing infrastructure. If a model could be made which does include existing infrastructure, it may turn out that routes proposed by the current model are not ideal. On the other hand, dedicated bus lanes can make a more straight line possible as proposed by the model, which is in line with the current implementation of the model. Since one of the characteristics of BRT is the use of dedicated bus lanes, the most direct route may be considered more realistic for BRT compared to a route which uses existing infrastructure.

The location of all stops must be considered as an indication, as these locations are realistically not ideal. They may not even be located at a street. The stops indicate in which postal code zones a stop could be located. The dashboard of Global BRT Data indicates that the average stop distance for BRT within the world is 811 meters. The spacing of the population centers of the zones naturally represents this average stop distance to some extent, indicating that taking the population center as indication for the location of a stop is not such a bad method.

The method for finding the most efficient route by skipping intermediate stops works well. However, the weights are made to be adjusted, but it was not determined what exactly is the right balance between travel time and the BRT Score. On top of that, a decrease in travel time may imply an increase in demand. Therefore it could be said that travel time deserves a relatively higher weight as its decrease may lead to higher demand. On the other hand, car travel time is not the best measure of determining the travel time on the BRT corridor, since it follows existing infrastructure, while as previously discussed, infrastructure dedicated to BRT may be built to reduce total travel time.

6.5 What are promising BRT corridors to and from Schiphol?

When comparing the results of the model for Schiphol with current plans for BRT within the Netherlands (Figure 19) it can be noted that the corridors between Hoofddorp and Alphen ad Rijn show up in both results. As discussed in chapter 7.3, it is assumed that corridors between parts of bigger cities may be more successful then between smaller villages because of the integration within the public transport network. Therefore the corridors between Schiphol and city zones within Leiden, Alphen ad Rijn and Hoofddorp seem most realistic.

6.6 Verification of the model

The biggest uncertainty found in the verification step was the data about public transport travel times. While the outliers were successfully limited in the final model, it decreases the accuracy of the model since some data had to be left out. How these outliers were retrieved by the API remains unknown, since manually calculating the travel times for these instances resulted in realistic travel times. In that sense, the API is a black box.

The sensitivity analysis shows that the model is stable for unseen data and reflects the relationships within the BRT Score formula correctly. It should be noted that an increase in population results in double the increase in BRT Score compared to increasing the amount of jobs. This makes sense since the population factor comes back twice in the formula. Multiplying the population factor with 0.5 is an option to balance this out, but since the population factor also describes travel demand for other motives than home-work the current relationships seem the best.

6.7 Validation of the model

While the input by the thesis supervisors was helpful, it is questionable whether this can be considered an independent expert view. It would be interesting to receive the opinion of an expert without a supervising role.

Comparing the results from the model with earlier proposed BRT plans was helpful. Within the study area, multiple shared BRT corridors were found, proving that the model can identify promising BRT corridors. This improves the model's validity. However, to further research the models validity it would be interesting to see the results if the study area included the whole of The Netherlands.

Documenting and uploading the model to sharing platform GitLab improves the models validity since every step can be understood by people with basic coding knowledge. Since the model could be applied to different study areas by different people proves that the model is general.

7 Conclusion

To conclude this report, the motivation, objectives and research questions of the research are summarized and answered.

7.1 Conclusion of the motivation

The motivation behind this research was to explore BRT possibilities in The Netherlands further, in order to find possibilities to expand the Dutch public transport network by finding BRT potential. The developed model explores BRT possibilities within the Randstad. However, BRT application within The Netherlands still lies far in the future, and is not only restricted by technical challenges but also political willingness. However, the results of the model might reveal promising BRT connections previously not thought of which could start a discussion.

7.2 Conclusion of the objectives

Objective 1: To construct a model for finding promising Bus Rapid Transit routes between city zones in the Randstad area

It can be concluded that both the general model and model for the Schiphol case show realistic results, based on the comparison with ongoing BRT plans within the Netherlands. Therefore the objective is reached, but to a certain extent, with the reasons named in the discussion section.

The main concern lies in the formula for calculating a BRT Score. As this name suggests, this says nothing about actual demand, but rather provides a suitability score. This score can only be used to compare all OD pairs within a specific study area. To get an idea about actual demand and possible ridership, an OD matrix for the study area must be constructed, which requires travel data for each zone. However, the formula for calculating a BRT Score is based on factors for BRT travel demand, so it can be said that OD pairs with a relatively high BRT Score do show potential.

Objective 2: To connect multiple city zones together to form a promising BRT line

The method of finding intermediate stops on a promising BRT corridor can be considered a medium effective approach of reaching this objective. The model does connect multiple city zones together on an already promising BRT line and shows that this results in a higher BRT Score, showing the 'pearls on a necklace' principle. However, the exact route and location of stops may better be determined manually in order to include all individual characteristics of this route.

Objective 3: To work out a case study for Schiphol Airport based on the developed model

Promising BRT corridors between Schiphol and zones within the study area were found, which seem realistic. However, the same constraints apply as with the general model. Since population is the main factor for simulating demand of each corridor, the model might be not accurate. More detailed data is needed to get a more accurate overview of demand. As already mentioned, constructing an OD matrix for Schiphol and surrounding zones would help estimate actual demand.

7.3 Conclusions of the research questions

What factors determine BRT travel demand between zones?

After reviewing literature about BRT and public transport demand, together with selecting on what factors would work for this research, the following factors were used in the model:

1. Number of residents
2. Number of jobs
3. Distance
4. Difference between car travel time and current public transport time

These factors try to describe travel demand as much as possible, but will not reflect the exact demand, as this relies on many other demographic, economic and geographic factors.

What do the zones look like which make up origins and destinations?

The origin and destination zones are described by the 4-numbered postal code system. The scale of this system is appropriate for this research, as it divides cities in city zones, while not being too small such that the model does not has to process very large amounts of data. Also, all necessary data to incorporate the factors chosen are available for this zone scale. However, the main problem with the postal code zone system is that it is made for mail distribution. As such, it may not be the best fit for describing travel demand.

What are promising BRT corridors within the study area?

The model successfully found promising BRT corridors within the study area. It can be concluded that most potential is found around Schiphol, Hoofddorp and south of Amsterdam. However, corridors around The Hague closely follow within the top 10.

In what way can intermediate stops be included in the model?

Intermediate stops are included in the model by applying Dijkstra's algorithm of finding the shortest path between intermediate points. Also, optimalisation helps find the most efficient route, by skipping stops. A consideration is made between travel time and BRT Score, of which the weights can be shifted according to which factor of the two has more priority.

What are promising BRT corridors to and from Schiphol?

The model results show promising BRT corridors between Schiphol and Alphen ad Rijn, Leiden and Hoofddorp primarily. However, it should be noted that population, distance and car and public transport travel time are the main factors for estimating the BRT Score.

8 Recommendations

First of all, it would be interesting to apply the model on the whole of The Netherlands. It would be particularly interesting to compare the BRT Scores of corridors within the Randstad with corridors in more rural areas. This would also help validate the model even more, as these model results can be compared with the national plans for BRT.

Researching whether similar datasets exist for countries outside The Netherlands can prove the suitability of the model for use in other countries. However, the formula for calculating the BRT Score, especially the cost factor, may need to be adjusted to local characteristics.

To further increase the accuracy of the model, more factors must be included in the model. For example, the number of students per zone could be included, or the exact location of hotspots such as stadiums or shopping centers.

A more accurate model for estimating BRT demand should be based on an OD matrix, which shows the actual number of trips between origins and destinations. Parts of the model from this research, such as the difference between car and public transport travel time, can still be used to find promising BRT corridors. However, using the OD matrix, exact estimations on demand and ridership can be given.

In order to create a successful BRT corridor with intermediate stops, research regarding the exact location of stops and needed infrastructural upgrades are necessary. The results of the model can be used to give an estimation of promising BRT corridors with intermediate stops, but as mentioned in the conclusion, an exact route is made on case to case basis.

9 Bibliography

Amsterdam Airport. *Amsterdam Airport - Schiphol (AMS)*. AMSTERDAM AIRPORT. https://www.amsterdamairport.info/

Armstrong, A. (2021). *dentifying the Factors that Influence Urban Public Transit Demand*. North Dakota State University.

De Wit, D. (2023). *A Framework for the proposal of Bus Rapid Transit in the Netherlands* [University of Twente]. https://essay.utwente.nl/96553/1/Wit-Daan-de.pdf

Decentrale OV Autoriteiten. (2022). *BRT plannen werkgroep BRT*.

Desaulniers, G., & Hickman, M. D. (2007). Chapter 2 Public transit. In *Handbooks in operations research and management science* (pp. 69–127). https://doi.org/10.1016/s0927-0507(06)14002-5

DOVA. (2022, oktober). *Manifest Bus Rapid Transit*. https://dova.nu/document/manifest-bus-rapid-transit

Gamas, J., Anderson, W., & Pastor, C. (2006). *Estimation of Trip Generation in Mexico City, Mexico, with Spatial Effects and Urban Densities*.

Global BRTData. https://brtdata.org/

ITDP. (2024, 28 maart). *What is BRT? - Institute for Transportation and Development Policy*. Institute For Transportation And Development Policy - Promoting Sustainable And Equitable Transportation Worldwide. https://www.itdp.org/library/standards-and-guides/the-bus-rapid-transit-standard/what-is-brt/

Jakobs, B., De Haan, F., Van Pijkeren, T., & Van Sluijs, D. (2019). *Met de bus langs de snelwegfile* [University of Applied Sciences Windesheim]. https://dova.nu/document/met-de-bus-langs-de-snelwegfile

Kennisinstituut voor Mobiliteitsbeleid. (2020). *Kansen voor Bus Rapid Transit in Nederland*. https://dova.nu/document/kansen-voor-bus-rapid-transit-nederland

Konečný, V., Brídziková, M., & Marienka, P. (2021). Research of bus transport demand and its factors using multicriteria regression analysis. *Transportation Research Procedia*, *55*, 180–187. https://doi.org/10.1016/j.trpro.2021.06.020

Ministerie van Infrastructuur en Waterstaat. (2019, december). *De potentie van Bus Rapid Transit in Nederland*. https://dova.nu/document/aanpak-brt-binnen-toekomstbeeld-ov

Randstad | Plaatsengids.nl. https://www.plaatsengids.nl/randstad

Rubio, F. (2023, 22 november). Pathfinding Algorithms- Top 5 most powerful. *Graphable*. https://www.graphable.ai/blog/pathfinding-algorithms/

Schiphol | Bijzondere beroepen op de luchthaven. Schiphol. https://www.schiphol.nl/nl/jij-en-schiphol/pagina/bijzondere-beroepen/#:~:text=Er%20werken%2065.000%20mensen%20op,meer%20verschillende%20banen%20op%20Schiphol.

Schofer, J. L. (2024, 6 maart). *Mass transit | Definition, History, Systems, Examples, & Facts*. Encyclopedia Britannica. https://www.britannica.com/topic/mass-transit

Svensson, P. (2020). *Designing bus route networks with algorithms* [KTH Royal Institute of Technology]. https://www.diva-portal.org/smash/get/diva2:1447174/FULLTEXT01.pdf

Tirachini, A. (2013). Bus dwell time: the effect of different fare collection systems, bus floor level and age of passengers. *Transportmetrica. A, Transport Science*, *9*(1), 28–49. https://doi.org/10.1080/18128602.2010.520277

Van Biezen, M. (2016). *Mechanical Engineering: Centroids & Center of Gravity (16 of 35) C. G. of a Composite Plate 1*. Youtube.

VTPI. https://www.vtpi.org/tdm/tdm132.htm

Wie zijn wij? | DOVA. DOVA. https://dova.nu/wie-zijn-wij