Coverage Practices in a Patronage Based Bus Network Design Process

A Case Study on Zuid-Holland Noord, the Netherlands

Johan Geurts

TU Delft

provincie Zuid-Holland

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By

J.R. Geurts

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Student number:	4292030	
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Thesis committee:	Prof. Dr. Ir. B. van Arem	TU Delft (CEG), chair
	Dr. Ir. N. van Oort	TU Delft (CEG), supervisor
	Dr. J.A. Annema	TU Delft (TPM), supervisor
	R.A. Haverman	Provincie Zuid-Holland
	S. van der Vliet	Provincie Zuid-Holland

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Preface

After just over 8 years my student life is coming to an end. When I started with my Bachelor of Industrial Design and Engineering, I had completely different expectations of what I wanted to do with my study. At some point, this changed and I switched to a Master of Transport, Infrastructure and Logistics. During my time at the TU Delft, I have changed and grown so much, which resulted in this thesis project in cooperation with the Province of Zuid-Holland.

This project would not have been the same without the help of my graduation committee. I would like to thank everyone of this committee. Niels, without whom, I might have ended up doing a completely different project. When I asked you little over a year ago for some tips to get started with my thesis project, I did not expect that this conversation would have led to multiple possible project opportunities. Our conversations during the project were very relaxed and really helped to improve the final results. I would also like to thank Jan Anne for his always constructive feedback. Your critical eye for the report was very helpful in how to communicate so much of the report. Furthermore, I would like to thank Bart for always acknowledging the importance of my mental health during the several meetings we had. This really helped me in at least try to take some breaks and take my mind of the report when necessary. Moreover I would like to thank Ronald and Sebastiaan of the Province of Zuid-Holland. During the first conversation with Ronald, you had a big smile the entire time that you kept for the entirety of this project. Your never-ending enthusiasm and positivity gave me a lot of confidence during the project. I would also like to thank you for getting me involved with the Snelstudie which allowed me to connect to the province despite working mostly from home. I would like to thank Sebastiaan for sharing his knowledge and experience of how public transport in Zuid-Holland is organized. You ensured that this research is not just some theoretical exercise but is also relevant from a policy perspective. I want to thanks the other colleagues from Zuid-Holland who were involved with the Snelstudie. It was great to be more involved with the province than just working on the graduation project. Moreover without the many ideas we had for the Snelstudie, I would not have come the models that were developed for this research.

Finally, I want to thank my friends and family for all of their support during the many months of this project. Special thanks to Helena, who was always there for me especially during the stressful moments. Your advice on improving my English, really helped to bring this report to the next level. This project might have lasted even longer, without you pushing me to make decisions on whether the models were good enough. Your support really helped me get through this project.

Johan Geurts
Delft, December 2021

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Abstract

The goals of bus services can be split into patronage (regarding the number of people that actually use the service) and coverage (regarding the number of people that are able to use the service) goals. Current bus networks are designed primarily for the coverage goals, as a consequence the patronage is lacking resulting in only few bus services to be cost-efficient. Literature provides several practices for increasing the cost-efficiency, but the effects on the coverage function are often neglected. This report follows a design process for a Dutch case in order to find how the coverage can be enhanced by including several new practices from the beginning of a network design. New design tools were developed in order to compare four different network designs relying on various coverage practices. The results show that a two layered system consisting of a high quality service combined with a supporting service in the form of a regular and/or demand responsive service is the best approach. Within the existing cost constraints, it is possible to create a large high quality network that relies on bicycles as access mode. By including shared bicycles, the coverage function is ensured while increasing the cost-efficiency of the network by allowing for faster routing. As a result, 10 percent more trips were made per timetable hour and 3 percent more passenger kilometres were covered. Replacing regular fixed line services by demand responsive services resulting in only a marginal increase that was highly dependent on the costs not to turn out higher. In combination with bicycle sharing, the results turned out to be much more positive with an additional 11 percent increase. By using a two layered system a high quality service can be provided that also serves a large coverage function. Of the supporting services, the use of shared bicycles allow for opportunities to improve even further, especially when combined with demand responsive transport.

Keywords: Public transport, Network design, Shared bicycles, Demand responsive transport, Bicycle-transit, Design approach

I. Introduction

In the Netherlands, public transport (PT) is important to reduce the strain on the road network. In order to do this, many passengers have to be attracted to the PT system, a goal which Walker (2008) describes as the patronage function. PT also provides a social service for the people unable to drive or ride a bike, which is described by Walker (2008) as the coverage function. The current bus services are primarily coverage focused, resulting in slow operations and only few services being cost-efficient. The costs per hour are high for bus services (CROW, 2015) and slow services attract few passengers. Covid further exposed this problem (CBS, 2020; KiM, 2020) resulting in an untenable system. In order to solve this, the patronage has to be increased, requiring stops to be removed and detours to be reduced, which negatively affects the coverage function. This friction causes a societal problem.

McLeod et al. (2017) reviewed current “best practices” for PT network design, however most research focused on increasing patronage functions with coverage practices rarely being used in practice. Similarly, Khan et al. (2021) investigated design practices in Sweden, but coverage practices were explicitly neglected. Contrarily, many theoretical coverage practices, as described by McLeod et al. (2017) and Cottrill et al. (2020), fit well within current technological trends (Van Oort, 2019), leaving a gap in the application of coverage practices and how they can be integrated with a patronage network. This research answers what the effects are of including coverages practices in the design process of a bus network, simultaneously offering insight in the opportunities of combining these practices for a real case area.

II. Methods

The research question of this study was answered by following several steps of the PT network design process described by Kepaptsoglu & Karlaftis (2009). First a generic design philosophy was described from which the objectives and criteria followed. Several design models and approaches were developed which were then applied to a case study.

A. Design Philosophy and Requirements

The design philosophy consisted of three parts. First, a selection of emerging practices was made based on their popularity in the plans of Dutch transport authorities. These practices were then split in patronage and coverage practices. Second was the creation of different usage segmentations for trip purpose, users and locations based on Dutch trip data. Finally, the works of Egeter (1993) and Van Nes (2002) were used in order to find where the to-be designed service fits in the overall hierarchy of PT. Using these three parts, a theoretical concept of different services was developed. In order to find the effects of different coverage practices on the patronage design process, multiple designs were made, each with a varying combination of the coverage services for this concept.

Using this theoretical concept, the requirements were developed. Both the objective and generic criteria were based on the existing requirements of the transport authority and the main goal of the transport company. A theoretical approach was used for the criteria of the individual services, based on common practices and literature from Van der Blij et al. (2010), Brand et al. (2017) and Rijsman et al. (2019).

B. Case Study

For this research a case study was used in order to determine the effects of the combination of patronage and coverage practices. The study area was supplied by the Province of Zuid-Holland (PZH). The area consisted of a section of the concession of Zuid-Holland Noord (ZHN). For simplification, a section of ZHN around Leiden was used as the main study area. An extra area consisting of aggregated NRM zones up to 5,5 km from the main study area was used that affected the network design. The resulting area is shown in Figure 1.

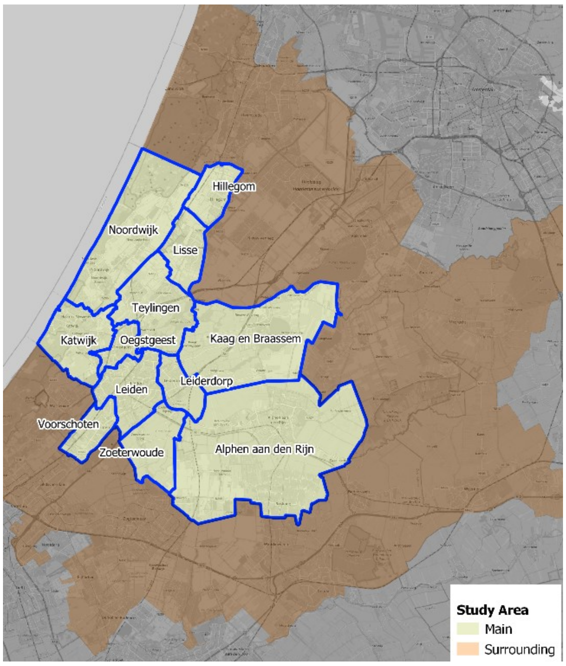

Figure 1: Main study area and surroundings.

C. Design Model and Approach

For the process of designing the bus networks, two models and an analytical approach were developed. Each performed a step in the design process: first determining the demand, then assigning stops and finally connecting all stops. The first model combined data from origin and destination locations to create a map of points with each a value for their relevance. The CBS Vierkantstatistieken, containing the number of inhabitants in squares of 100 by 100 metre (CBS, 2021), were used for the origin locations. For the destinations a varied set of data sources was used. Data from DUO (DUO, 2020, 2021) was used for the locations of secondary education. Internal data of PZH was used for industrial zones and office parks (PZH, 2019, 2020). The rest of the destinations were obtained from OpenStreetMaps.

Each location was assigned to one of the NRM zones. Overlapping locations were split up. For locations that did not have a value, i.e. number of students, a value was based on data from the NRM zones. The total value of the NRM zone for the related destination type was equally divided over the related destinations in the zone.

Each origin point was given a weight based on the number of inhabitants. Not everyone is able to access the same distance (Daniels & Mulley, 2013). In order to increase the coverage function, the inhabitants were split into age groups with each a different importance. The total weight of an inhabitant point was the sum of the number of inhabitants in each age group times their importance.

The total weight of the inhabitants was set as equal to the total weight of all destinations, which were split by trip purpose. Each trip purpose had a frequency given by CBS (2020b), which was used to determine the importance of the trip purpose. For each trip purpose the total value in the study area was determined. For each trip purpose the weight per value was determined by first dividing the importance [in %] of the trip purpose by the total weight of the origins. This was then divided again by the sum of all values of the trip purpose in order to create the weight per value for each trip purpose. The weight of each destination was calculated by multiplying the value of the destination by the weight per value of the corresponding trip purpose. Finally, both the origins and destinations had the same total weight.

The second model used these weight points in order to determine ideal locations for stops. For this, a weighted K-Means clustering algorithm was used. The found cluster centres showed the ideal locations for bus stops. However, this required many iterations to find the ideal number of clusters and the best fitting set of clusters. Therefore, an addition to the algorithm was made focussing on the zones with the most weight. The number of clusters in this zone was increased by one and the weight points within an acceptable distance according to the criteria to a cluster centre were seen as served. Then, a new zone with the most unserved weight was chosen. This was repeated until enough percentage of the total weight was served. The resulting cluster centres were ideal stop locations, however most were not reachable by bus. Therefore, the stop locations were moved to logical roads nearby. Because this changed the ideal locations and percentages, new iterations were required taking the determined stops into account as predefined cluster locations. Different stop types corresponding to the different services were determined using this model.

Lines were drawn through these stops based on the most popular origin-destination (OD) combinations according to the NRM. This was again done through multiple iterations. Each iteration, line segments were added for the OD combinations with the most unserved trips. Determining whether a trip was served or not was done based on the weight points. For each combination of origin and destination weight points the distance and the potential PT travel time was calculated. The trip was seen as served if either the distance was within a set threshold or the VF (Van Goeverden & Van den Heuvel, 1993) was below 3.

The same approach was used in order to estimate the number of passengers and passenger kilometres. For this, only the trips above the set distance threshold were included. The VF curves of Van Goeverden & Van den Heuvel (1993), shown in Figure 2, were used to estimate the modal split between car and PT for the remaining trips, which then resulted in the number of passengers. The passenger kilometres were calculated by multiplying the estimated number of passengers for each combination of weight points by the distance between these points.

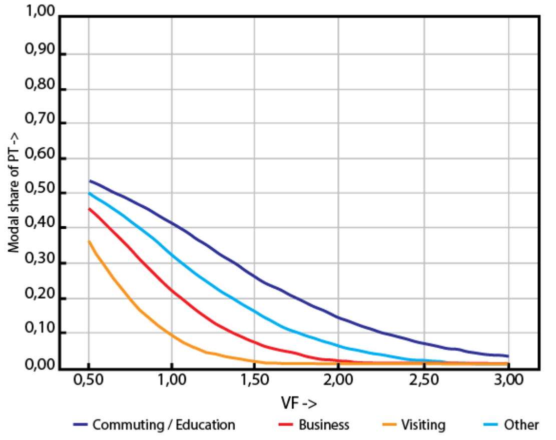

Figure 2: VF curves for several trip purposes (Adapted from: Van Goeverden & Van den Heuvel, 1993).

III. Results

A. Context and Goals

The patronage practices focused on increasing the speed and frequency of PT, resulting in high quality services. In order to accommodate this, the stop density had to decrease because this allowed for more direct services, reducing the number of detours. Transfers were incorporated at specific transfer hubs which also connected to coverage services. The emerging coverage practices consisted of providing facilities for access (and egress) by (shared) bicycle and using demand responsive transport (DRT) instead of regular fixed lines. Combining the two types of practices led to a theoretical network concept as in Figure 3.

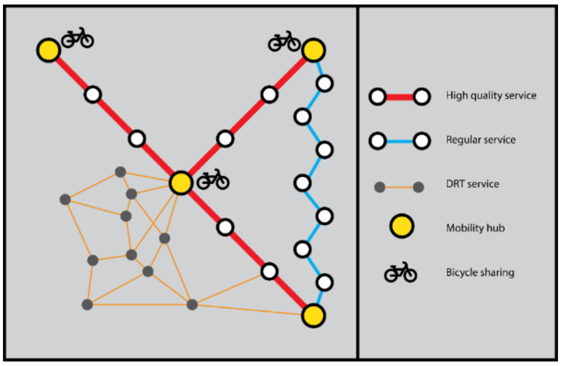

Figure 3: Schematic network example with the practices included.

Commuting is the trip purpose that usually gets most attention (Schwanen et al., 2001), however this only accounts to a fifth of all trips (CBS, 2020b). Figure 4 shows the distribution of all different trip purpose both in total and for the distances for which the bus is most commonly used. This showed that attention must also go to other destinations than workplaces. Elderly, who are often more reliant on PT (Bakker & Van Hal, 2006), made relatively more shopping and service trips, meaning that for the coverage function these destinations were even more important. Potential for feedering by bicycle was even larger in rural than urban regions because the distances covered by bike were already larger (CBS, 2020a).

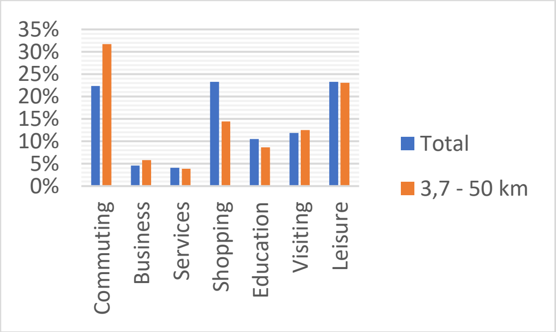

Figure 4: Relative frequencies for each trip purpose in Zuid-Holland in 2019 (CBS, 2020b).

The new services consisted of two layers: a fast and frequent high quality (HQ) service that offered express urban and local interurban connections and a supporting service consisting of either DRT or regular fixed lines connecting to the high quality service. The objective for the new bus networks was maximizing the number of trips served by PT, within the criteria that the maximum amount of timetable hours (TTH) could not exceed the TTH of the existing network (which was 1601 for the study area (Arriva, 2018)). At least 80% of the total weight had to be served by the HQ service, with 95% by any service within the distances given in Table 1 and Table 2. DRT stops had feeder distances of 400m based on the existing criteria for low frequent services. The HQ service had to have a frequency of at least an average of 4 times per hour (KiM, 2018) which was lower than advised by APTA (2010) and Van der Goot (2010), but higher than currently achieved by most R-Net services (allGo, n.d.; Arriva, n.d.; Connexxion, n.d.; EBS, n.d.-a, n.d.-b, n.d.-c; GVB, n.d.; Qbuzz, n.d.; RET, n.d.). For the regular lines, this had to be at least twice per hour to be an improvement upon the DRT service.

Table 1: Overview of criteria per level of urbanization for a high quality service.

Level of urbanization	**Distances in metres**				
	Access	**Egress by bike**	**Egress by walking**	**Egress to hospitals**	**Egress to shopping areas**
Highly urbanized	1100	1100	700	500	500
Urbanized	1200	1200	750	500	500
Moderately urbanized	1300	1300	800	500	500
Little urbanized	1400	1400	850	500	500
Not urbanized	1500	1500	900	500	500

Table 2: Overview of criteria per level of urbanization for a regular service.

Level of urbanization	**Distance in metres**			
	Access	**Egress**	**Egress to hospitals**	**Egress to shopping areas**
Highly urbanized	450	450	200	450
Urbanized	500	500	200	450
Moderately urbanized	550	550	200	450
Little urbanized	600	600	200	450
Not urbanized	650	650	200	450

B. Model Application

Using the models and approach that were developed, four different network designs were created: one without any emerging coverage practices (1), one using DRT services (2), one using shared bicycles (3) and one with both DRT services and shared bicycles (4). The HQ services for both designs without shared bicycles were the same and those that used shared bicycles were also the same. Figure 5 shows these HQ services for the designs without shared bicycles and the corresponding regular service. Figure 6 shows the alternative stops for these HQ services when the regular lines were replaced by DRT. Figure 7 and Figure 8 show the same but for the designs with shared bicycles.

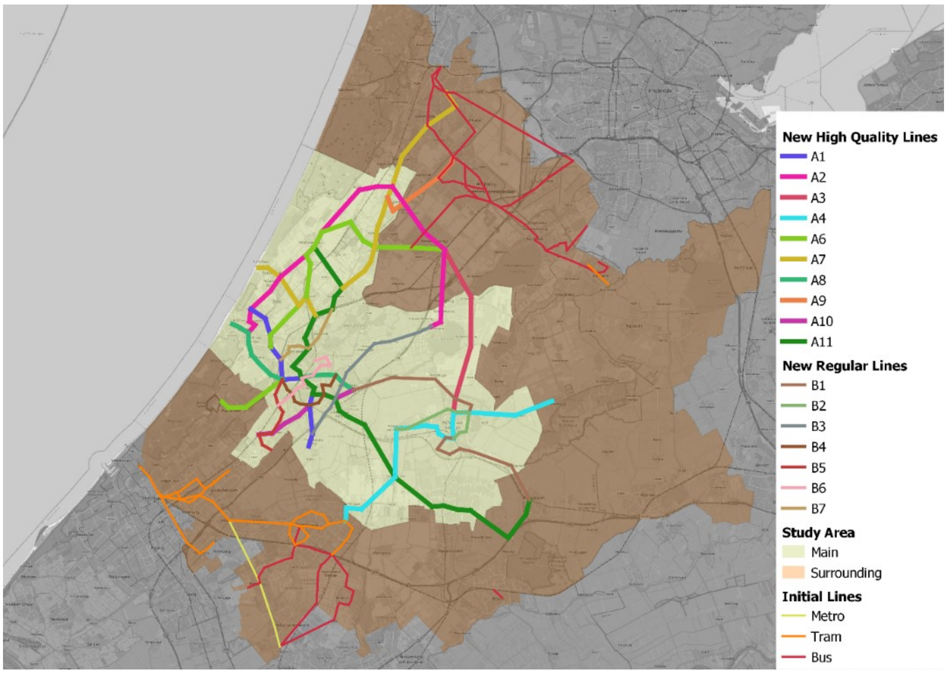

Figure 5: High quality service without shared bicycles and regular fixed lines.

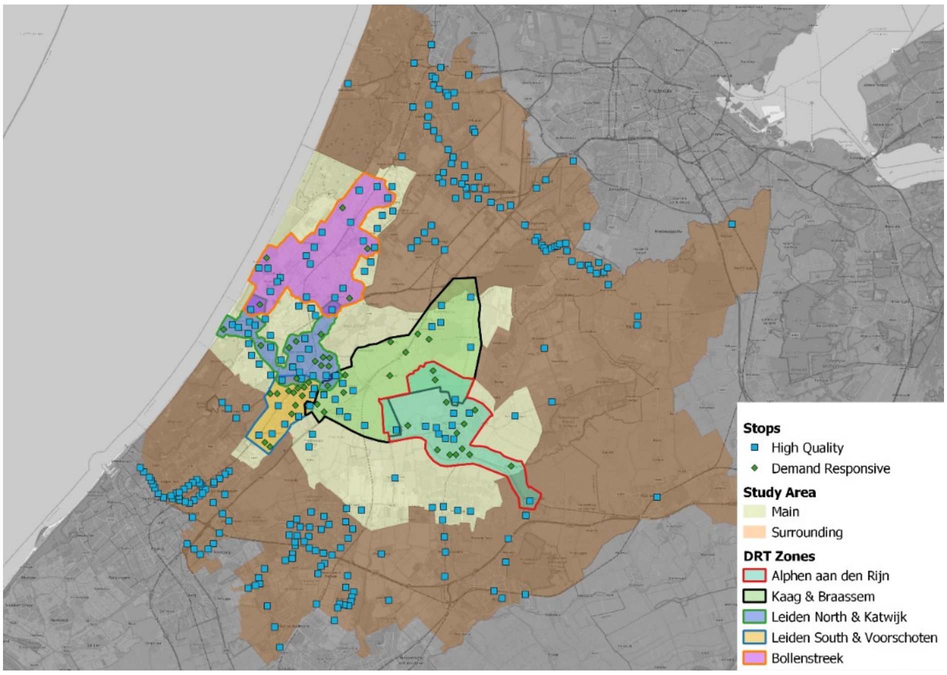

Figure 6: Alternative stops for a demand responsive service supporting the high quality network without shared bicycles.

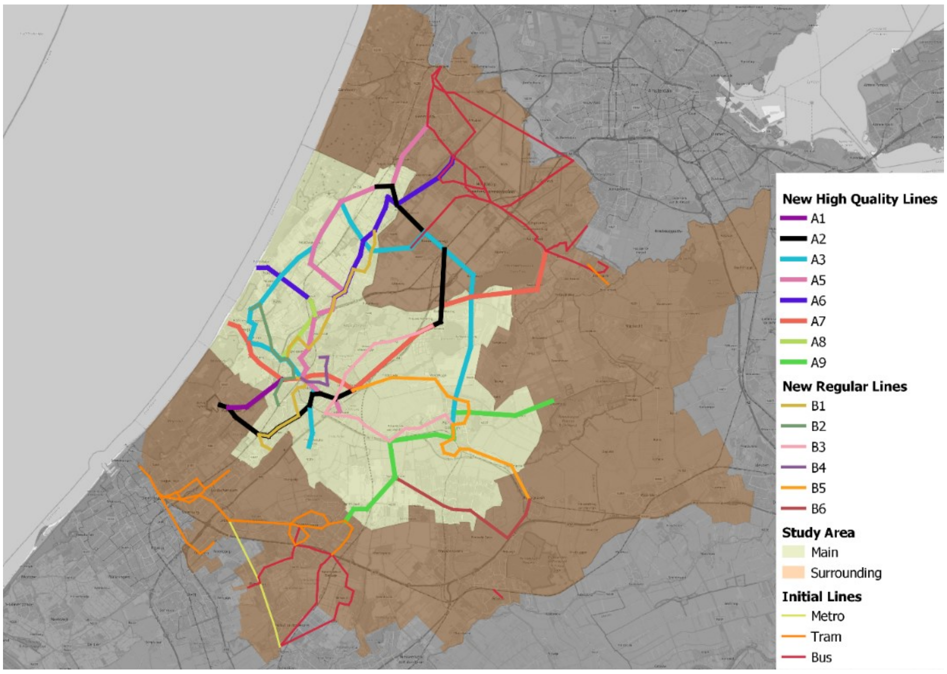

Figure 7: High quality service with shared bicycles and regular fixed lines.

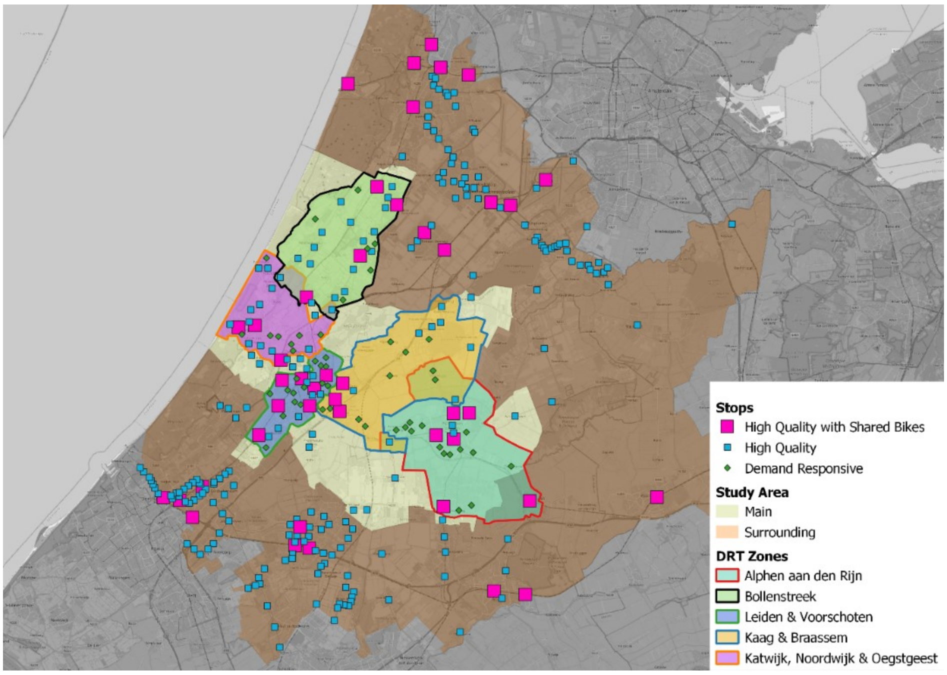

Figure 8: Alternative stops for a demand responsive service supporting the high quality network with shared bicycles.

Also, two baseline networks were used which incorporated only the train services and the HQ bus, tram and metro (BTM) services of the surrounding region. One baseline did include bicycle sharing and one did not. For the comparison of the new networks, the corresponding baseline results were subtracted and the resulting trips and kilometres were divided by the number of TTH in order to compare the efficiency of the four designs. Table 3 gives the TTH and the trips and passenger kilometres per TTH for each design. The improvements when only replacing regular service by DRT services were 2% for the number of trips and 1% for the amount of kilometres. The use of shared bicycles increased the number of trips by 10% and the amount of kilometres by 3%, which was increased further by 11% when DRT services were also included. The effects of DRT services were very dependent on the costs of the DRT service. Without shared bicycles, a small increase in costs would have led to a negative effect, but where shared bicycles were introduced the costs of DRT could have been up to 2,5 times as high before regular fixed lines were more cost-efficient.

Table 3: TTH per design and results per TTH

	TTH used	**Trips per TTH**	**Kilometres per TTH**
Design 1: no shared bikes and no DRT	1589	6,16	85,91
Design 2: no shared bikes but with DRT	1462	6,30	87,16
Design 3: shared bikes but no DRT	1602	6,76	88,64
Design 4: shared bikes and DRT	1370	7,52	98,75

IV. Evaluation and Discussion

There were two sources of limitations for this research. First were the criteria which affected the outcome. The percentages of weight to be served affected the number of stops required. Higher percentages result in more stops and thus a higher stop density and as a consequence more detours and lower speeds. On the other hand, the feeder distances that were used were very conservative, especially Brand et al. (2017) showed that potential for longer feeder distance. Longer feeder distances would have resulted in less stops and thus faster lines. If these distance were less conservative the effects of especially the use of bicycle sharing would have been larger. DRT by itself only had a small positive effect, but this was very dependent on the costs not to turn out higher than assumed. The second source of limitations were the computational costs of the models and approach, making it impossible to compare the designs to the existing network. Data for many destinations was missing resulting in them being excluded. Difference in size of the NRM zones resulted in a bias towards large zones during the drawing of the lines. The estimation of the number of trips excluded many possible trips that were either too short, from too far outside the study area, or had a larger feeder distance than acceptable according to the criteria. This second source however did not limit the ability to compare the different designs to each other. Most of these would have benefited the use of shared bicycles when included in the calculations.

V. Conclusions and Recommendations

Including coverage practices into the design process of patronage based bus networks affects all steps of this process. The philosophy of these networks relied on a foundation of HQ services, resulting in greater acceptable feeder distances in the criteria. Providing cycling facilities and DRT and/or regular fixed lines complement this foundation by offering coverage practices allowing the HQ to not require full coverage of the service area. The four designs showed that this foundation including supporting services was possible within the given TTH. The use of shared bicycles allowed for a lower stop density resulting in even faster lines, attracting 10% more passengers and 3% more passenger kilometres that were not taken by car. This was increased further by 11% when the supporting regular lines were replaced by DRT services. When shared bicycles were not used, the positive effects of DRT services were very low unless the costs of DRT turn out to be lower than assumed.

For future research, it is recommended to gain more insight in the costs and criteria for DRT to improve the reliability of the DRT results. Furthermore, improvements to the model have to be made to confirm the results found. These improvements include developing better insight in the optimal stop locations, making the OD zones more similar in size, and reducing the computational effort of the network evaluation in order to allow for more trips to be included. This would then also allow for these models to be used for comparing effects of different criteria on different regions.

For policy makers, this research provides insights in the opportunities that arise when the access and egress distances are increased by relying more on the use of the bicycle as both access and egress mode. A vast network of high quality services is possible when this is done. With a relatively small number of additional services the coverage function is provided much more efficiently, allowing the network to be more effective in providing the patronage function.

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Table of Content

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List of Abbreviations

DRT: Demand Responsive Transport

MaaS: Mobility-as-a-Service

NRM: Nederlands Regionaal Model (Dutch Regional Model)

OD: Origin-Destination

PT: Public Transport

PZH: the Province of Zuid-Holland

ZHN: the concession of Zuid-Holland Noord

1. Introduction

In the current situation, bus services are operated with the goal of providing an accessible service for as many locations as possible, which Walker (2008) describes as the coverage function of a public transport (PT) service. In order to fulfil this goal, bus lines currently contain a lot of detours, making the service fairly slow. According to CROW (2015) more than half of the operating costs goes to the bus driver, meaning that slower services are less cost-efficient than faster ones. Combined with the knowledge that passengers generally prefer shorter travel times, this results in relatively high operating costs with only a few passengers to make up for this as these slow services will likely cause them to use other modes of transport. Attracting passengers is described by Walker (2008) as the patronage function of a PT service, which the existing bus service realizes rather poorly. Although inefficient, this was not a large problem until the Covid pandemic caused an enormous drop in passenger numbers (CBS, 2020f) and therefore a large drop in revenues, straining bus operators until passenger numbers return to pre-Covid levels, which will take at least until 2025 (KiM, 2020). In an attempt to survive, bus operators choose to reduce service levels to a minimum in an attempt to cut costs, which ironically lowers passenger numbers even further, potentially causing a downward spiral leaving only minimal services with no patronage function at all.

On the other hand, the volume of road traffic is expected to be ten percent above pre-Covid numbers in 2025 (KiM, 2020). With an increasing number of inhabitants and a growing economy, the number of travel movements is expected to keep on increasing past 2025. Without PT as a viable option, a much larger share of travels will be made by car, straining the road network, which is problematic because in the Netherlands very little space is available for expansion of this network. PT is much more space-efficient (Walker, 2012). This strain can therefore be relieved if more travellers use PT, requiring the patronage function of PT to be strengthened. Literature already shows how this can be done with widely accepted and utilized practices, but all of these come at the cost of the coverage function, which is usually ignored, as can be read in Chapter 2. Contrarily, research on emerging first and last mile practices that improve the coverage function is limited to either theoretical examples or cases where the practices were added on an existing PT network. These new practices, which fit well with current technology trends, show an opportunity to take over the coverage function from existing slow fixed lines in the network. However, case studies that include these new coverage practices in the PT network design from the beginning do not exist. From a societal perspective, a call for change has arisen to enhance the patronage function of bus services. The approach on how to do this is already known, but how to include the emerging coverage practices in a new network design remains unknown, leading to the following research question:

What are the effects of including coverage practices in designing a patronage based bus network for a real world case in the Netherlands?

In order to answer this question, a case study was conducted (see also Section 3.1). In this case study, a design process for a bus network was executed taking both patronage and coverage practices into account. The four steps of the network design process of Kepaptsoglou & Karlaftis (2009) were used as a guideline to create several sub-questions. An additional step was included at the start in order to develop a theoretical description of the new bus service: this explains what role the bus takes in the larger mobility system. Based on this theoretical description, the objective and criteria were established in the second step. Hereafter, the area characteristics for the case study were defined. Depending on the objective, the criteria and the area characteristics, several bus networks were created. Finally, the different networks were compared to each other. Each of these steps correspond to one of the following five sub-questions:

1. **What is the design philosophy of the bus service?**
   This sub-question consists of multiple parts, which, when combined, describe the role of the new bus service in the larger mobility system. First, the different practices that were used in the design process were determined. Also, several segmentations were created based on trip, traveller, and geographic characteristics to gain insight in different needs for different trips, travellers, and areas. Finally, the place of the bus service in the existing public transport hierarchy was determined.

2. **What are the objective and criteria of the bus network?**
   The objective for the bus network is to focus on the patronage function performance, as most real world case studies focus on this function as well and the societal challenge is to strengthen the patronage function. The coverage function was obtained from the criteria of the bus network. These criteria were based on the findings in the previous sub-question.

3. **What are the characteristics of the study area?**
   The characteristics of the study area consist of demand and supply characteristics. In the demand characteristics, an overview was composed of where demand for mobility exists. The supply consists of the PT services that are outside of the scope of the case study, such as train services and bus services in areas around the main study area. The demand of the locations served by these other services, within the chosen criteria, was reduced in order to find where the demand for new bus services was located.

4. **What are possible bus network designs?**
   Four different bus network designs were created based on the earlier determined objective and criteria as well as the area characteristics. In each of the designs, a different set of coverage practices was included.

5. **How do the different designs perform and differ from each other?**
   The performance in terms of "number of passengers" and "total passenger kilometres" was calculated for each of the designs, which were then compared to determine the effects of the different practices. These effects showed how effective the practices were in increasing the patronage, while adhering to the criteria for the coverage functions.

The structure of this report is as follows: first, in Chapter 2, an overview is given of the existing literature in regard to current design practices and problems. Chapter 3 describes the methods that were used to answer the research question and the corresponding sub-questions. Then, the individual sub-questions were answered starting with the design philosophy in Chapter 4, followed by the objectives and criteria in Chapter 5. The area characteristics are determined in Chapter 6. Using these earlier results, four bus networks were designed in Chapter 7 and compared in Chapter 8. Finally, the conclusion with the answer to the main research question is presented in Chapter 9, which also includes the discussion and recommendations.

2. Literature Review

The literature review of this report consists of three parts: the design process, the design problems, and the emerging practices. Section 2.1 focusses on describing and understanding the general design process of a public transport network. Then in Section 2.2, the most important problems and dilemma's that are generally found during the design process, are described. Finally in Section 2.3, literature on the emerging practices that are aimed to solve these problems and dilemmas, is discussed. From the literature on the emerging practices a research gap appeared, which is presented in Section 2.4.

2.1. Design Process

The complete process of planning, operation and control of a bus service system consists of the following seven mathematical problems: (1) network design, (2) frequency setting, (3) timetabling, (4) vehicle scheduling, (5) driver scheduling, (6) driver rostering and (7) real-time control (Ibarra-Rojas et al., 2015). The optimal solutions of each of these problems rely on the solutions of the others, therefore they are ideally solved at the same time. However, the individual problems are too large to be solved at the same time. In order to find the best solution possible, the problems are often solved in consecutive order. According to Ibarra-Rojas et al. (2015), the network design, frequency setting, and timetabling problems largely use the same inputs. As this is the case, several methods have been developed to combine two or all of these three problems into a single problem (Guihaire & Hao, 2008), as can be seen in Figure 2.1. The different methods of combining these problems are the following:

- In the Transit Network Design and Scheduling Problem (TNDSP), all three of the problems are merged into a single problem. This requires scaling down or simplifying a lot in order to keep the problem manageable.
- The Transit Network Design and Frequency Setting Problem (TNDFSP) is a combination of both the network design and the frequencies setting problems. This combination leaves the timetabling problem for a next step.
- The Transit Network Scheduling Problem (TNSP) is solved for an earlier determined network design and aims to provide a solution for both the frequencies setting and the timetabling problem.

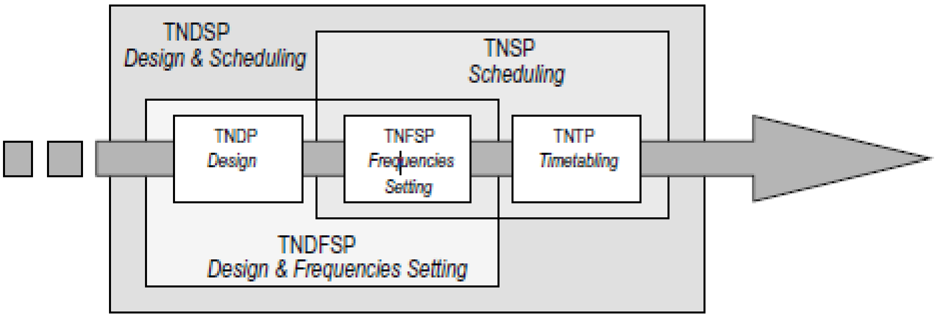

Figure 2.1: Structure of different transit network problems (Guihaire & Hao, 2008).

Given the fact that this research is done for the Province of Zuid-Holland, focus is mostly on the design and frequencies setting problems: timetabling is done by the operators. For this reason only the TNDFSP and the consecutive solving of the design and frequencies setting is further examined in this literature review. This network design process consists of the following four steps: (1) establishing the goals and objectives; (2) defining the road structure, demand patterns and characteristics of the area for which the network will be designed; (3) developing network alternatives; (4) evaluating the different network alternatives (Kepaptsoglou & Karlaftis, 2009). The main inputs in this design process are the network of existing infrastructure and the estimated demand (Farahani et al., 2013). Depending on the specific approach, other inputs can be used, such as available budget, bus capacities, constraints on the total number of lines, a set of predefined possible lines, requirements on the round trip time of the lines, frequencies, maximum number of stops, minimum coverage of the demand by the network or a maximum number of transfers. If the frequencies setting is included to solve the TNDFSP, the inputs of fleet size and the minimum frequencies are also required. There are several considerations that can be used for the establishing of the goals and objectives. These are the dependency on existing routes, area coverage, route and trip directness, demand satisfaction, number of lines or the total length of all routes combined, the shape of the network, the number of total runs and frequency bounds (Guihaire & Hao, 2008; Farahani et al., 2013).

2.2. Design Problems

Regardless of the design process used, two opposing clusters of goals exist: patronage goals and coverage goals (Walker, 2008). A patronage goal is generally dependent on the number of travellers that use PT. A coverage goal is achieved by the availability of a PT service, regardless of the number of PT users. A network designed for patronage primarily serves trips with a large demand for a majority of travellers. On the other hand, a coverage network serves as many locations regardless of the demand while taking the limitations of all travellers into account. In the development of the exact network, four trade-offs between different desires and abilities of the traveller have to be made. Egeter (1993) describes the trade-offs as the following four design dilemmas:

1. The trade-off between access time and in-vehicle time: a low stop density (i.e. a small number of stops per square kilometre), as shown in the upper section of Figure 2.2, allows for fast services and thus a short in-vehicle time. Contrarily, a high stop density, as shown in the lower section of Figure 2.2, offers a nearby stop for many locations and therefore a short access time; however, more stops and detours slow down the service, increasing the in-vehicle time. Slower services also require more vehicles and drivers to operate a given frequency than faster services. A high stop density helps more in fulfilling the coverage goals, because the service becomes more accessible for more people and locations can be served that are otherwise too far away. For the patronage goals, a low stop density is more desirable, because less kilometres have to be driven and most travellers prefer the shorter in-vehicle times and higher frequency (KiM, 2018).

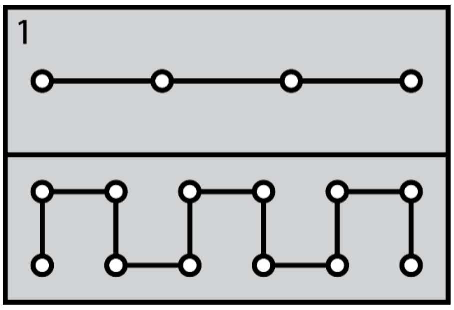

Figure 2.2: Design dilemma one, trade-off between access time and in-vehicle time.

2. The trade-off between waiting time and in-vehicle time: a high network density (i.e. the amount of links per square kilometre), as given in the right section of Figure 2.3, consists of many direct routes between locations, leading to short in-vehicle times. Consolidating the links results in a network as given in the left section of Figure 2.3, allowing for high frequencies and thus short waiting times, because all resources are used for few sections. However, this comes at the cost of the in-vehicle time, because all trips between corner locations go through the centre. In a patronage network only routes with a high demand are offered, thus a low network density is used.

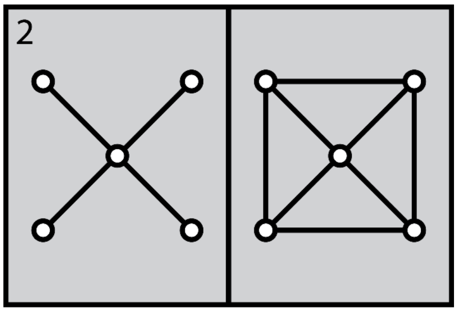

Figure 2.3: Design dilemma two, trade-off between waiting time and in-vehicle time.

3. The trade-off between waiting time and the number of transfers: the number of individual lines operating the different links can also be varied. Using few different lines, as shown in the left section of Figure 2.4, allows for high frequencies on each line; however, not for all trips a service without transfer is available. When more lines are introduced, as shown in the right section of Figure 2.4, transfers are not necessary, but the frequencies of each line drops, resulting in either higher waiting times or still requiring transfers.

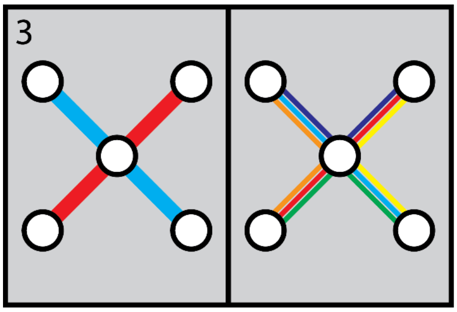

Figure 2.4: Design dilemma three, trade-off between waiting time and number of transfers.

4. The trade-off between travel time and the number of transfers: a bus network can consist of multiple levels, as shown in the right section of Figure 2.5. Having multiple network levels results in a shorter travel time on the higher levels, but more transfers between the network levels are required. When only one level is used, all resources can be spend on either the coverage or the patronage goals. Multiple levels allow for more compromises between both goals by distributing the resources over the levels that fit the different goals.

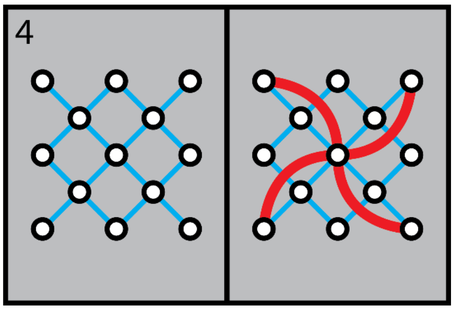

Figure 2.5: Design dilemma four, trade-off between travel time and number of transfers.

2.3. Emerging Practices

In a search to find the best public transport planning practices, Khan et al. (2021) investigated the design practices of the six regions that had the largest increase in passenger numbers in Sweden. In this report, it is found that most of the regions focussed on investing and simplifying high-demand routes to increase their speed and frequency. This is in line with the best practices of the literature review of McLeod et al. (2017). This paper concludes that for a public transport network to be effective, it has to be legible, coordinated, and frequent. Furthermore, lines have to serve multiple destinations and utilize transfers to increase the range of services across the region. Practices like these have the aim to enhance the patronage, as described by Walker (2008). On the other hand, Khan et al. (2021) specifically chose to ignore any coverage practices. Many of the case studies referenced by McLeod et al. (2017) also focussed on improving the patronage of PT networks. Although McLeod et al. (2017) did include a section called “new technology and complementary nontraditional PT”, only a very small number of case studies is mentioned. In this section informal services and on-demand modes, such as demand responsive transport (DRT) and bicycle sharing, are presented. These practices show potential to help achieving the coverage goals by providing first and last mile services. The recent improvement of communication technology increases this potential even further (McLeod et al. (2017), especially when combined with other trends such as information, automation, and sharification (Van Oort, 2019). The potential of such flexible systems is underpinned by Cottrill et al. (2020), provided that these systems are reliable, well-integrated, affordable and have enough information available. However, the integration of these systems is mostly researched for existing network designs, but these networks are not designs with these practices in mind. Little literature exists that attempts to design a PT network with these practices integrated (Tavassoli & Tamannaei, 2019). A purely theoretical multimodal future that takes these systems into account is proposed by McLeod et al. (2017), which is shown in Table 2.1. Proposal like these are, however not yet combined with actual network designs.

Table 2.1: Potential future public transport network multimodality.

Core, High capacity network	Publicly managed investments	Private investments
Grade separated heavy rail	Demand responsive transit routes	Taxis, on-demand chauffer services, ride sharing, car sharing
Light rail, Bus rapid transit, Strategic / targeted local bus routes	Bike share, pedestrian realm improvements, cycle networks	Autonomous (self-driving), electric cars

2.4. Conclusions

For the design of public transport systems, there are two main groups of goals that oppose each other; patronage goals and coverage goals. Design practices focussed on achieving patronage goals have been researched extensively and have proven themselves successful in attracting more passengers. Practices such as bicycle sharing and DRT help to achieve the coverage goals. Literature on how these practices can be included in new PT network designs is very limited, as in most literature these practices are only applied on existing networks. At the same time, there are trends that increase the potential of these practices, allowing for further incorporation in the design process. The knowledge gap is that it is unknown what the effects are of introducing coverage practices, such as bicycle sharing and DRT at the beginning of the design process.

3. Methods

In this chapter, the methods that were used in this research are presented and discussed. First, a case study is introduced in Section 3.1. Then, the methods used for each sub-question the methods are described in Section 3.2.

3.1. Case Study

The knowledge gap found in the literature review states that there is a lack of research done on the effects of including emerging coverage practices in new bus network designs. In an attempt to fill this gap, a case study was used because it provides a more realistic image of the problems and opportunities that arise during the design of a bus network. Because of the societal challenge of increasing the patronage function while keeping up the coverage function, the Province of Zuid-Holland (PZH) provided the concession of Zuid-Holland Noord (ZHN) to be used for this case study. Figure 3.1 shows ZHN compared to other concessions in the Dutch Randstad region.

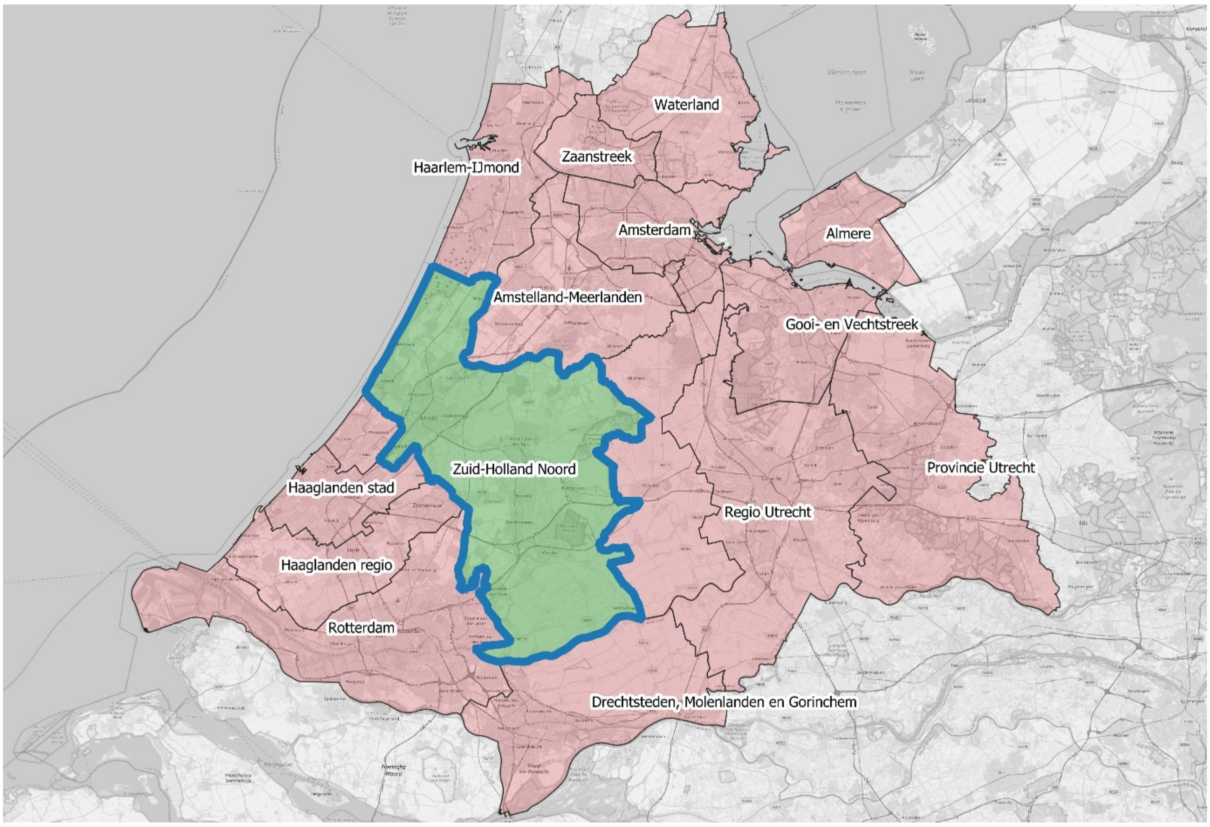

Figure 3.1: The concession area of Zuid-Holland Noord and neighbouring concession areas in the Randstad (OpenStreetMap contributors, n.d.; PDOK, 2020).

For this report, a section of this concession was used as the main study area in order to simplify the design process. A region surrounding the city of Leiden was chosen as the main study area. This region, as shown in Figure 3.2, consists of the municipality of Leiden and several other municipalities with a close proximity to or a strong focus on the city of Leiden. Despite the size reduction, the resulting study area is similar in size as many of the other concession areas from Figure 3.1. All lines of bus networks that were designed in this report, were either fully in or connecting to this study area. New lines completely outside of this study area were not proposed, because this was outside of the scope of this report.

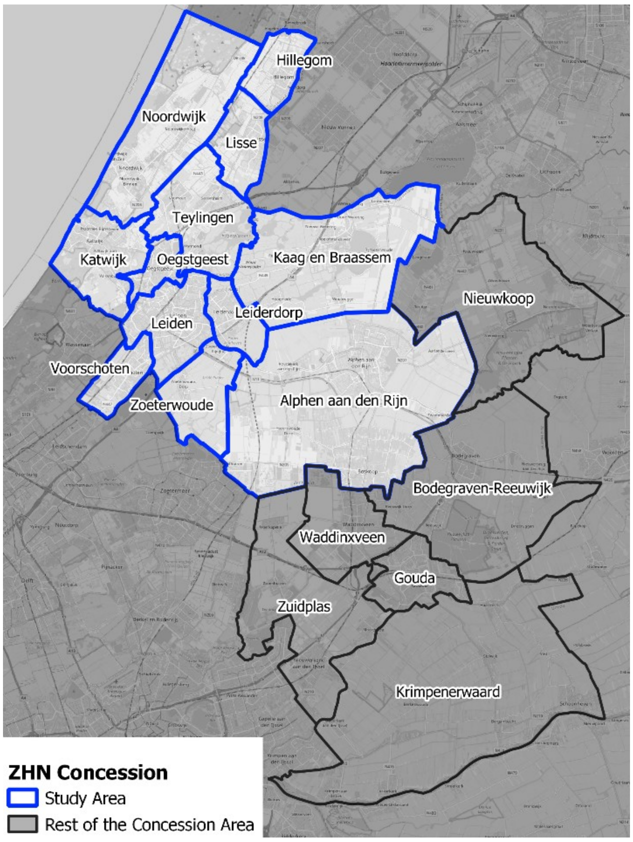

Figure 3.2: The municipalities in the main study area (OpenStreetMap contributors, n.d.; PDOK, 2020).

3.2. Sub-questions

Aside from the use of a case study, other methods were used as well. In this section, the methods and approaches of each sub-question are presented. Each section corresponds with one of the sub-questions as presented in Chapter 1.

3.2.1. Design Philosophy

Developing the design philosophy was done in three steps: determining the practices to be included, developing segmentations, and deciding on a hierarchy. Using the plans of each transport authority in the Netherlands, a list was compiled of common emerging practices that affect the network design. A reduction was made by removing little mentioned practices and practices that are combinations of multiple other practices. The remaining practices were divided in patronage and coverage practices. A short analysis based on literature and existing services was performed to find how each practice is best implemented and what effect it has on the criteria.

Segmentations were developed for trip purposes, traveller age groups, and geographic zones. The trip purposes as defined by CBS (2020d) were used. For each of these trip purposes, the frequency of trips that are relevant for the bus, was determined. Then, travellers were segmented by their age groups using CBS statistics (2020b). By focussing only on the total frequencies of each trip purpose, the differences between different groups is lost. These differences affect the coverage function of the network because some trip purposes are only or more relevant for specific groups. In order to find these differences, the frequency of each trip purpose was determined for each age group. Finally, segmentations were made for geographic zones based on the level of urbanization to find similar differences. Applying these segmentations to different land use areas resulted in different characteristics which were used to set specific criteria and to determine where to use which practice.

A hierarchy was defined between the different services with characteristics for each hierarchical level, using the works of Egeter (1993) and Van Nes (2002). The hierarchical levels have to fit within the context of the study area, so within the corresponding scale and considering existing rail services. This was combined with the different segments to find what areas fit the different hierarchical levels.

Finally, a complete design philosophy was described based on the findings of the practices, segmentations and hierarchy. This philosophy provides a description for each hierarchical level what service is provided, including additional supporting services. As well as a description for what passengers are expected for each level.

3.2.2. Objective & Criteria

The objective and criteria ensure the functions of the bus network. With the problem as described in Chapter 1, the goal is to improve the patronage function without losing the coverage function. Therefore, the objective focussed on increasing the patronage and the criteria guarantee the coverage function. Two groups of criteria were generated; general criteria and criteria based on the design philosophy. The general criteria consists of criteria that have to be met for the bus network as a whole (i.e. maximum amount of service hours, minimum percentage of inhabitants served). These general criteria are based on the current network and criteria. The philosophy based criteria consist of criteria for minimal frequencies and maximum access and egress distances specific for each service, region and destination. These criteria were based on scientific literature or, when a clear scientific picture is missing, on what is acceptable in the current network.

3.2.3. Area Characteristics

Area characteristics are divided into two groups: demand and supply characteristics (Kepaptsoglu & Karlaftis, 2009). The supply characteristics consisted of the transport supply in the study area (i.e. existing public transport services). Data, consisting of stops served, frequencies, and travel times, for this supply, was acquired from the relevant public transport operators . The demand characteristics consisted of the locations people live and the locations people want to travel to. In this report, Origin-Destination (OD) matrices of the NRM[1] were available on roughly postcode-4[2] level for three trip purposes (commuting, business and other). For each zone in the NRM, the number of inhabitants for several age groups and jobs for several types was also given. However, these zones are often large to determine where demand exists. To get a better insight, a more detailed image was created by including the CBS Vierkantstatistieken (CBS, 2021a), which contain the populations for several age groups in either 100 by 100 meter or 500 by 500 meter squares. In this report, the smallest squares were used, because they give a more detailed picture of the exact locations of inhabitants. A disadvantage of these smaller squares is that, if the number of inhabitants is less than 5, no inhabitants are given for privacy reasons. For the larger squares this is also true, albeit less common. However, the demand would be very low if these numbers where included, thus limiting the negative effects.

For the demand of each trip purpose, which were found in the segmentations of Section 4.2, multiple different types of destination were used. Although many types exist, data was for most too limited to be included in this report, the types that were include are shown in Table 3.1. For commuting three different destination types were used. Geographic data, including useable floor space, was available

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[1] Dutch Regional Model: for this report the predictions for 2030 were available as well as the base year of 2014

[2] Dutch postcodes consist of four numbers followed by two letters: postcode-4 consists of the postcodes with the same combination of the four numbers, which corresponds roughly to a large neighbourhood or a small village

for both the office parks (Provincie Zuid-Holland, 2019) and the industrial areas (Provincie Zuid-Holland, 2020b). For each NRM zone, the corresponding job data was spread over the floor space of these locations in the NRM zone, using the "DIENSTEN" (business services) jobs for the office parks and the "INDUSTRIE" (industrial) jobs for the industrial areas. The locations of these two destination types was only available for PZH, but for neighbouring zones in Noord-Holland such locations were not available. This limitation had to be kept in mind throughout the design process. Locations of shops on the other hand were available for the entire study area by using OpenStreetMap (n.d.) data. Using the "DETAIL" (retail) jobs of the NRM, a similar approach was used to determine the number of jobs per shop. Because no size indications were included in the data of the shops, the NRM jobs were spread evenly over all shops in a zone, resulting in all shops being treated the same regardless of their actual size. In most zones, shops were clustered, so the effects of distinguishing between individual shops would have been small.

Table 3.1: Destination types for each trip purpose.

Commuting	**Business**	**Services**	**Shopping**	**Education**	**Leisure**	**Visiting**
Office parks	Office Parks	Hospitals	Shops	University buildings	Sport facilities	Inhabitants
Industrial areas	Industrial areas	City halls		Secondary schools	Restaurants	
Shops					Museums	
					Zoos	
					Amusement parks	

The destination types of the business trip purpose were the same office parks and industrial areas as for commuting. Similarly for the shopping trip purpose, the same data for shops was again used. For the services trip purpose, hospitals and city halls were included. The locations of these destinations were again obtained from OpenStreetMap (n.d.). Contrary to the other destination type, no differentiation between individual hospitals and individual city halls were made in order to maintain their societal importance. The education trip purpose contained two destination types: university buildings and secondary schools. For other destinations not enough data was available. The locations of university buildings were once more acquired from OpenStreetMap (n.d.). Using the number of university students available from the NRM zones, the same method was used to determine the number of student per building as used for the commuting destinations. The locations of the secondary schools was only available on a postcode level (DUO, 2021). Using the geographic centres of the postcode zones (CBS, 2021b), an estimation for the locations was made. For most secondary school locations, the exact number of students was available. For the schools where this number was not available, the average number of all schools was assumed. For the leisure trip purpose, several different destination types were included, which were all collected from OpenStreetMap (n.d.). Large differences in the demand for each data point existed: for the sport facilities each individual court and field was included as individual data points whereas each amusement park and zoo as a whole also consisted of single data points. These differences were dealt with during the calculations of the overall demand. Finally, for the visiting trip purpose the number of inhabitants were used again. In Appendix E detailed images of all these locations in the case study area are given. In order to combine all these data points, a model was developed which assigns a weight for each of the data points.

The weight assignment model that was developed, combined all these data sources into a single dataset. First, all data was assigned to the right NRM zones. When data points with a given value (i.e. inhabitants or floor space) covered more than one zone, the data point was split over each zone with each a new value. Equation 3.1 shows how these new values were calculated. Figure 3.3 shows this part of the model schematically.

$$Value_{inZone} = \frac{Area_{inZone}}{Area_{Total}} * Value_{Total} \tag{3.1}$$

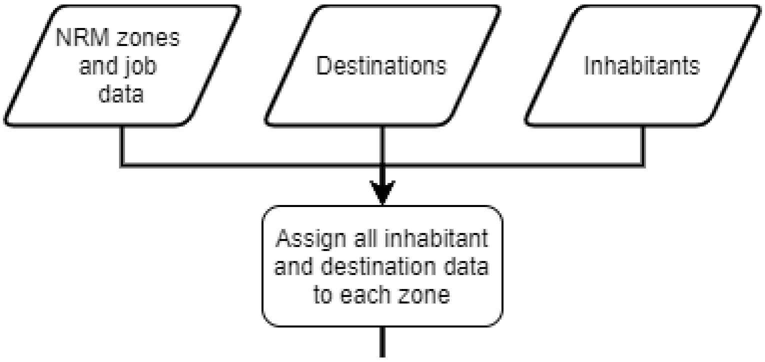

Figure 3.3: Assigning all location data to the right zones in the weight assignment model.

In the next step, the weights for the inhabitant data were calculated. Because the acceptable access distances varies per age group, as is discussed in Section 4.2.2, the demand for nearby public transport varies as well. Using the inverse of these acceptable access distances, the weight for inhabitants with a shorter access distance was increased in order to allow for the coverage goals to be more easily achieved. In order to calculate the weight of each inhabitant data point, this inverse was multiplied by the number of inhabitants in the corresponding age group and then summated over all age groups, as shown in Equation 3.2. This process is shown in Figure 3.4 as part of the weight assignment model.

$$InhPointWeight = \sum_{i \in Age\ Groups} \frac{1}{AccDist_i} * Inh_i \tag{3.2}$$

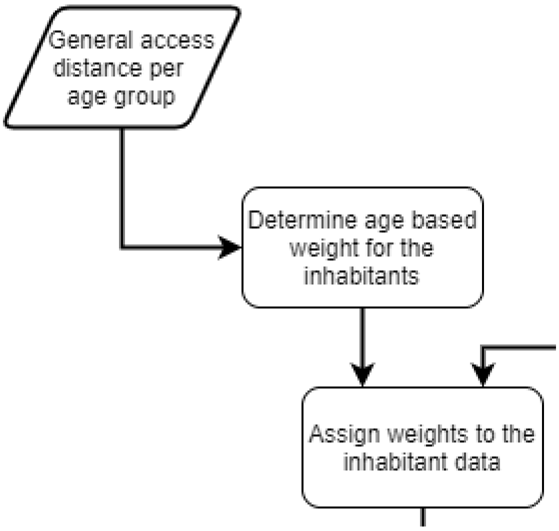

Figure 3.4: Determining the weights of the inhabitants in the weight assignment model.

The weight assignment for the destinations was done differently because of the variety in data. First, the NRM data (i.e. the job data and the number of university students) was divided evenly over the corresponding destinations in each NRM zone, as shown in Figure 3.5. Then, the importance of each individual destination within the trip purpose was determined. For the commuting, business, and shopping trip purposes, the destination importance consisted of the number of jobs at each destination. The importance of each educational destination was equal to the number of students. The distribution of the importance for visiting destinations was the same as that of the inhabitants and between service destinations no differentiation was made, so all these destinations had the same importance. Contrary to the destinations of all other trip purposes, for leisure destinations no initial differentiation between destinations existed other than their type, while this was required. An arbitrary importance to each type of leisure destination was given with the museums and restaurants used as a baseline: a zoo or an amusement park counted for 20 museums or restaurants and sport facilities counted for a tenth of a museum or restaurant. Ideally, this would have been based more objectively on for example visitor numbers or club memberships, but this data was not available. Therefore, the importance of the leisure destinations was likely under- or overestimated.

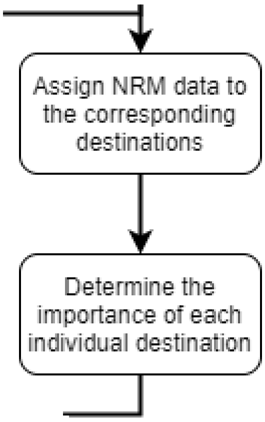

Figure 3.5: Determining the importance of each individual destination within their respective type for the weight assignment model.

The distribution of the importances of the trip purposes was largely the same as the number of trips made for each trip purpose as a percentage of the total number of trips. The only difference was that the "service" trip purpose was split into a "hospital" and a "city hall" trip purpose, because these destinations have a larger societal role than number of trips alone. These two new trip purposes received both the same importance as the "service" trip purpose would have gotten. The total percentage of all trip purpose went over 100 percent as a result of this division. Using Equation 3.3 the importances were calculated such that the sum of the importance of each trip purpose adds up to 100 percent. Figure 3.6 shows the section of the model that corresponds to this process.

$$Importance_{TP} = \frac{RelFreq_{TP}}{\sum_{TP} RelFreq_{TP}} \tag{3.3}$$

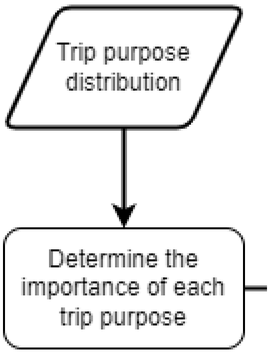

Figure 3.6: Determining the importance of each trip purpose in the weight assignment model.

Finally, the weights of all destinations were determined, as shown in Figure 3.7. In this step, the importance (in percentages) of each trip purpose was multiplied with the total inhabitant weight to calculate the total weight that was distributed over each trip purpose. Equation 3.4 gives a summary of this calculation. In this calculation, trips were assumed to be only between a home and a destination. This assumption made the calculations much easier because the total weight of the destinations could therefore be assumed as equal to the total weight of all inhabitants. In reality, many trips between destinations exist as well. The weight of each individual destination was determined by first calculating the weight per importance value (i.e. number of jobs, number of students, and so on) and then multiplying this by the importance value of each destination corresponding to the trip purpose. Equation 3.5 gives this second step in the calculation of the weights of each individual destination. A set of weight points (for both the inhabitants and the destinations) for each NRM zone resulted from these calculations. The different model sections for the complete weight assignment model which is given in Figure 3.8.

$$TotalWeight_{TP} = Importance_{TP} * \sum_{INH} Weight_{INH} \tag{3.4}$$

$$Weight_{T_{DP}} = \frac{TotalWeight_{T}}{\sum_{DP} Value_{T_{DP}}} * Value_{T_{DP}} \tag{3.5}$$

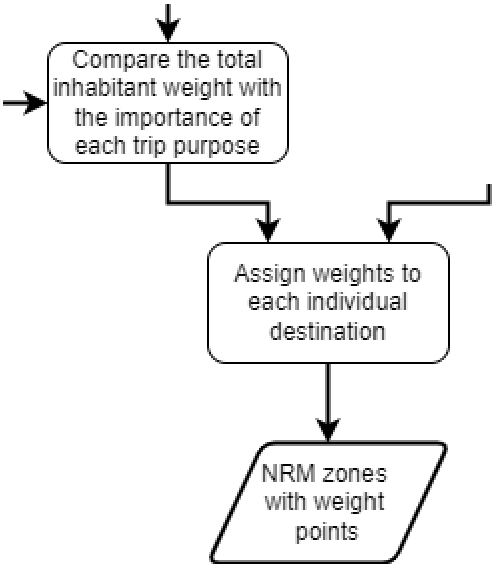

Figure 3.7: Comparing the importance of each trip purpose with the inhabitant weights and assigning weights to each individual destination in the weight assignment model.

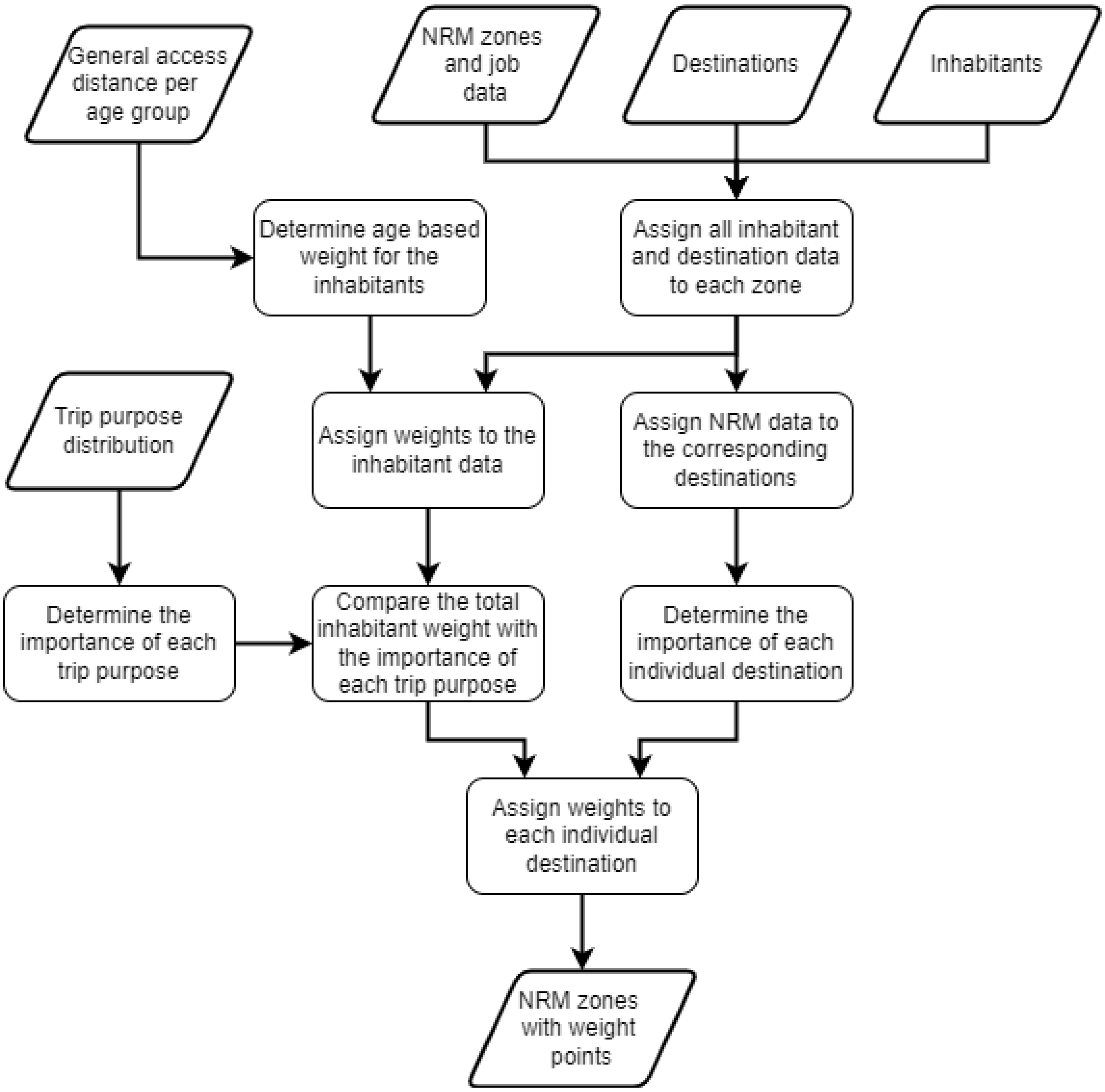

Figure 3.8: The complete weight assignment model.

3.2.4. Network Designing

Four bus networks were designed by first determining the locations of the bus stops of the new network and then drawing lines between these stops. Each of these four designs incorporated different coverage practices. A model building upon the weight assignment model was developed for determining the stop locations. The results of the weight assignment model were a set of points with each a weight assigned. Bus stops are ideally placed at locations that serve as much weight as possible. A weighted K-Means clustering algorithm finds clusters of weighted points by finding a centre for each cluster with a minimal weighted distance to each point in the corresponding cluster. This algorithm fitted very well with the input (the weighted points) and the goal of finding optimal locations between these points. Therefore, the weighted K-Means clustering algorithm was used as a basis for the stop location model. The locations resulting from the clustering algorithm were usually not reachable by bus. More realistic locations were manually assigned using these results as input. Because these manual adjustments affected the rest of the results, the model was made to be solved iteratively.

The first step for each iteration was to determine which points were and were not already served by either higher level stops (i.e. train stations) or stops placed in earlier iterations. For this process, more inputs than the weight points and the sets of stops were used, as shown in Figure 3.9. The criteria for the access and egress distances were also required in order to determine whether a point was served sufficiently. Because these distances were too far for some people to access or egress, points were only seen as 100 percent served if they were within a short distance of a stop. For longer distances within the criteria, 90 percent served was used. By calculating the distance to the closest stop, if any, for each data point, it was determined how much, either 100 percent, 90 percent or 0 percent, the weight of the data point could be reduced. The remaining weight represented the demand that was not yet served sufficiently by a public transport stop.

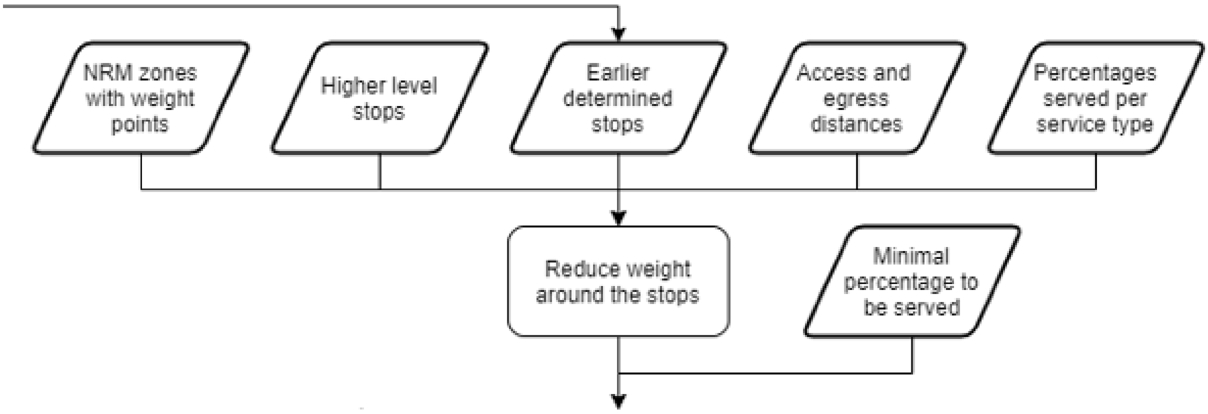

Figure 3.9: Reducing weights around existing and earlier determined stops in the stop location model.

Then, it was decided whether enough demand was served or more stops were required. In order to make this decision, the total remaining weight in the study area was divided by the initial total weight without any stops, as shown in Equation 3.6. If the resulting percentage was smaller than the minimum given by the criteria, more cluster centres (i.e. new possible stop locations) had to be determined. Figure 3.10 shows the steps that were taken for adding more clusters. A regular weighted K-Means clustering algorithm becomes very slow when more clusters are added, therefore the algorithm was only executed for a small section of the study area during each time a cluster was added. The section was chosen by taking the NRM zone with the most weight left unserved. In this section with several neighbouring zones the algorithm was executed with a number of clusters that was increased by one. The weight in the zones was reset to initial levels and reduced again assuming the resulting cluster centres as new stop locations. Using these new weights, the percentage of served weight was again calculated. When necessary more cluster were added using this method.

$$Perc_{Served} = 1 - \frac{\sum_{Point} Weight_{Point}^{Remaining}}{\sum_{Point} Weight_{Point}^{Initial}} \tag{3.6}$$

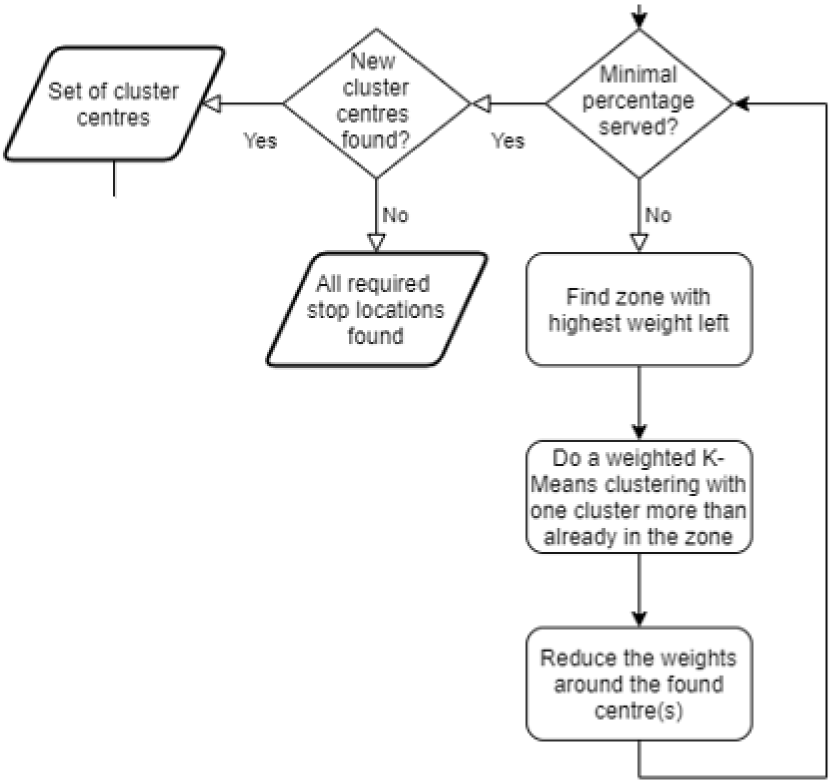

Figure 3.10: Create new cluster centres for the stop location model.

Using the found cluster centres, stop were located using the steps shown in Figure 3.11. For each centre, the weight that was served, was calculated. Stops were placed on logical roads only near the cluster centres that served a sufficient amount of weight. Earlier determined stops were also analysed during this process. If the weight served by a stop could be increased enough[3] by offering shared bicycles, the stop was upgraded to include this service.

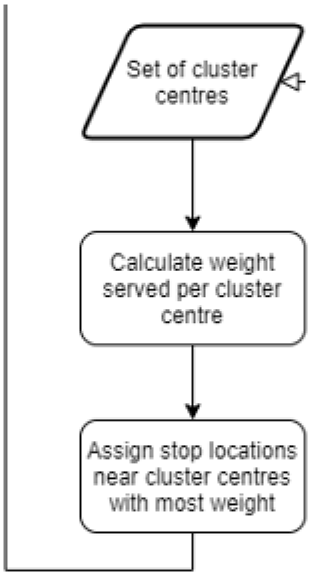

Figure 3.11: Assigning stop locations based on cluster centres in the stop location model.

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[3] In this report, an increase of 0,25 percent of the total initial weight in the main study area was assumed as "enough"

The complete stop location model is shown in Figure 3.12. The aforementioned steps were repeated until no new cluster centres were required to fulfil the minimal percentage of served weight. This model was used for each level of service, starting with the highest hierarchical level. For the each lower level, the earlier determined higher level stops were included in the set of "Higher level stops". Lower level stops were later upgraded to higher level when a higher quality lines passed these stops.

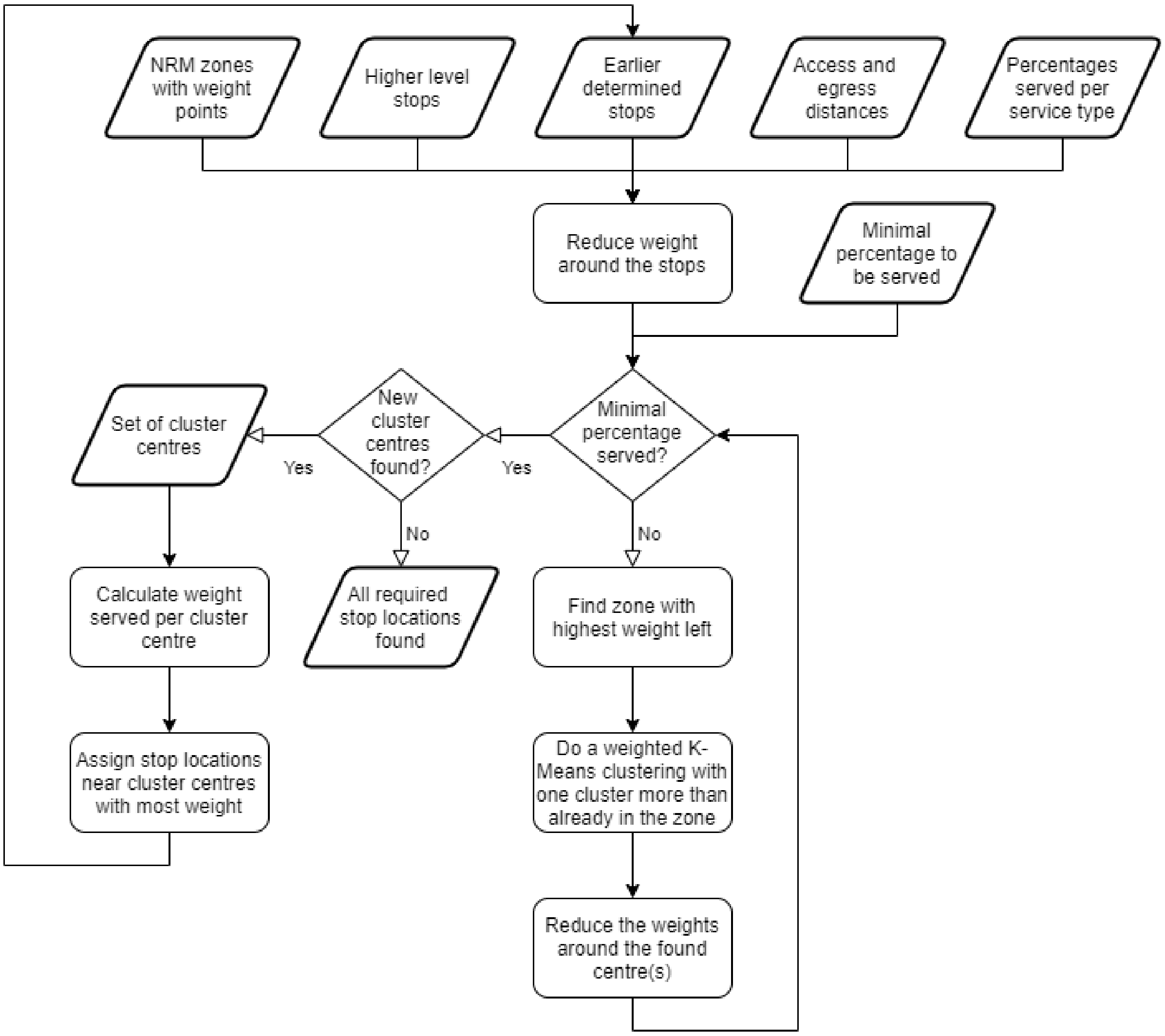

Figure 3.12: The complete stop location model.

After deciding on the locations of all stops, lines were drawn through all these stops using an analytical method. Although this approach did not result in an optimal solution, the calculations were much easier and faster. Lines focussing on patronage were drawn based the number of trips between the NRM zones. New lines or line extensions were introduced between NRM OD pairs with the most trips that were not walkable or cyclable and not yet served by PT. During this process the number of trips between other zones was also affected because of new transfers or neighbouring zones of the OD pairs that were also served by the new line segments. Therefore, the number of unserved trips was recalculated after drawing several new line segments, resulting in an iterative process. Lines focussing on coverage were drawn between closely located stops regardless of the number of trips.

During the creation of the lines an adjusted set of weights for the data points was used, which was similar to those used in the stop location model but without differentiation between different age groups. The differentiation was made to enhance the coverage of the stops by increasing the weights of the age groups that were not able to cover longer access or egress distances. Using the same weights would increase the number of trips made by these age groups as well. Therefore, during the creation of the lines an adjusted set of weights for the data points was used. If the combination of inhabitant point and destination point was seen as "served", a percentage of the total trips between the zones was subtracted equal to the percentage of the inhabitant weight in the zone times the percentage of the destination weight in the other zone. In order to determine whether these trips were served or not, the straight distance between each inhabitant point and each destination point in both OD zone was measured. If this distance was lower than 1000 metres the combination was assumed to be walkable and trips between these points were completely served. Trips could also be cyclable which depended on the average cycling distance in each level of urbanization of the origin of the trip. Trips with distance between 1000 metres and the distances given in Table 3.2 were assumed to be cyclable, which meant that for most travellers the trip could be made by bike. It was assumed that roughly 10 percent of these trips could not be made by bike, so these trips were only served for 90 percent. The remaining 10 percent was seen as served if a PT option was available that was faster than walking. Trips longer than these distances could only be seen as served if a PT service was available.

Table 3.2: Average distance of a cycling trip for each level of urbanization (CBS, 2020c).

Level of urbanization	**Average distance of a cycling trip (in m)**
Highly urbanized	3790
Urbanized	3830
Moderately urbanized	3940
Little urbanized	4210
Not urbanized	4780

For the availability of PT, the access and egress distances had to be within the given criteria. If this was the case, the weighted travel time was calculated using Equation 3.7. The total weighted travel time consisted of the access time, the waiting time, the time in the vehicle, and the egress time. Transfer time was included in the waiting time. Each of these times was multiplied by a weight factor, given in Table 3.3, to improve the realism of the travel behaviour. Although these factors are relatively old, they still give a good indication of the order of magnitude. More exact values were not necessary, because it was not the focus of this paper to come with travel times for all trips accurate to the minute. The access and egress times are calculated using the distance to and from the stops. For the 90 percent of travellers that were able to use a bike, the average cycling speed of 10,88 km/h in PZH (CBS, 2020e) was used for the access time and, if shared bicycles were available at the egress stop, also for the egress time. The average walking speed of 4,94 km/h in PZH (CBS, 2020e) was used for the calculations of the egress time at stops without shared bicycles, the access and egress times of the coverage services, and, if the distance to the stop was walkable, for the access time of the remaining 10 percent of travellers. The waiting time consisted of the average waiting time at the stop, assuming passengers would arrive at random, and the total transfer time. The in-vehicle time was calculated used the total driving time of each line segment and an average waiting time of 30 second at each stop. The driving time for each line segment was estimated based on the driving times between both stops during both the morning and evening rush hours according to Google Maps.

$$t_{total} = W_{access} * t_{access} + W_{wait} * t_{wait} + W_{in-vehicle} * t_{in-vehicle} + W_{egress} * t_{egress} \tag{3.7}$$

Table 3.3: Travel time weight factors (Van der Waard, 1988).

Weight type	**Factor**
W_{access}	2,2
W_{wait}	1,5
$W_{in\text{-}vehicle}$	1
W_{egress}	1,1

For the 10 percent of the travellers that were assumed to be unable to cycle, the OD combination was seen as "served" if the speed resulting from the weighted travel time was faster than the walking speed. For the rest of the travellers, a more strict threshold relying on the VF[4] value was used. The VF value compares the travel times by car and by PT. The travel times by car were calculated using the speeds given in Table 3.4. Because these speeds vary greatly between distance groups and level of urbanization, multiple values for the speed were used contrary to the single values for cycling and walking which did not vary significantly. Up to a VF value of 3, PT plays a role in attracting travellers, although lower VF values are preferable. Because PT only plays a very marginal role above a VF of 3, this value was chosen as a cut-off for an OD combination to be considered "served".

Table 3.4: Average car speeds (in km/h) per level of urbanization and trip distance (CBS, 2020e).

Distances (in km)	**Highly urbanized**	**Urbanized**	**Moderately urbanized**	**Little urbanized**	**Not urbanized**
0 – 1	10,00	6,00	9,23	9,23	9,23
1 – 3,7	12,57	14,53	15,71	16,23	17,09
3,7 – 7,5	18,50	21,26	22,39	25,75	25,98
7,5 – 15	25,75	28,38	29,68	31,99	33,38
15 – 30	35,67	39,11	39,92	41,46	43,97
30 – 50	46,86	49,95	52,32	50,10	47,56
50 – 75	60,26	56,99	60,62	62,01	58,85

Lines were added and extended until the criteria for the maximum number of timetable hours was met. The number of timetable hours of each line was calculated by multiplying three factors: the total driving time (including the total stopping time at each intermediate stop), the average hourly frequency, and the average time between the first and the last service (i.e. the operating time). The first factor differed for each individual line and the other two were service type specific. The timetable hours for the DRT service were calculated by multiplying the number of vehicles that were used times the average length of the service.

3.2.5. Performance & Comparing Designs

The performance of each network was determined using the VF curves of Van Goeverden & Van den Heuvel (1993). Although this method only gives a rough estimate, it did not require any data of the performance of existing PT network, which allowed for a much faster estimate of the number of passengers. The VF curves, as shown in Figure 3.13, were available for four different groups of trip purposes. The same calculations as during the line creation phase were used, but, instead of a binary choice of being served or not, the modal share of PT corresponding to the VF value was used. In other words, the number of trips for any OD combination that was seen as being served by PT was multiplied by the modal share of PT in order to estimate the number of trips that would actually be made by PT.

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[4] "Verplaatsingstijdfactor" or travel time factor: the factor between the travel time by PT and by car. A VF of 1 means that car and PT are equal and a VF of 2 means that the car is twice as fast

For further simplifications, the VF curves were split in several line segments between the points given in Table 3.5. The passenger kilometres for each pair of data points were also calculated by multiplying the number of trips by the straight distance.

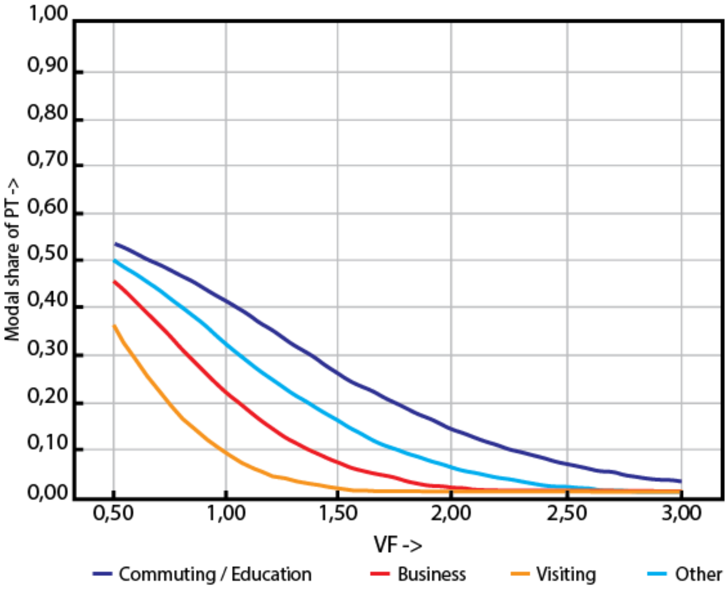

Figure 3.13: VF curves for several trip purposes (Adapted from: Van Goeverden & Van den Heuvel, 1993).

Table 3.5: Share of public transport per VF.

VF	Commuting	Business	Visiting	Other
0	0,53	0,47	0,38	0,50
0,5	0,53	0,47	0,38	0,50
1,0	0,41	0,21	0,09	0,34
1,5	0,28	0,08	0,02	0,19
2,0	0,15	0,03	0,01	0,08
2,5	0,09	0,01	0,01	0,03
3,0	0,04	0,01	0,01	0,01

These calculations were first executed for two baselines without a bus network in the study area, only train services and bus, tram, and metro services in the surrounding area were included. One of the baselines also included existing shared bicycles at several train stations. Subtracting these baseline results from the results of the four network designs allowed for better comparison between the designs without the results being affected by trips that did not include any of the designed bus services. The remaining number of trips and passenger kilometres were at least partially performed using the design networks. Because the number of timetable hours differed between the designs the results were divided by the timetable hours to determine the trips per timetable hour and the passenger kilometres per timetable hour. The effects of the different coverage practices were determined by the comparison of these final results.

4. Design Philosophy

A single philosophy for the different bus network designs was described based on three different parts. First in Section 4.1, different practices were chosen to be included and grouped in patronage and coverage practices. For each practice a small literature study was performed. Then in Section 4.2, different segmentations are discussed. By looking at these segmentations, differences were discovered which were used in Chapter 5 to either increase or decrease strictness of criteria for some of these segments. In Section 4.3, the general hierarchy and the roles of the PT networks is presented. Finally in Section 4.4, the philosophy is presented which was used to base criteria on.

This chapter does not focus primarily on the case of Zuid-Holland Noord but provides a theoretical philosophy that could be applied for any case in the Netherlands. However, some of the data used in the segmentations does focus on Zuid-Holland. In other areas in the Netherlands, small variations occur because Zuid-Holland contains a lot of urban area compared to other provinces affecting some of the travel patterns.

4.1. Emerging Practices

The emerging practices that were included, were based on literature combined with practices that are currently emerging in the Netherlands. McLeod et al. (2017) presents several practices for both the patronage and the coverage goals of Walker (2008). These practices rely on a core network of mostly rail and high quality bus services, supplemented with demand responsive transport and a bicycle network for both access and egress of the core network. In order to find the relevant practices for cases in the Netherlands, an overview of the transitional plans of the Dutch transport authorities by Rosdorff (2021) was used. In Table 4.1 the practices reported in this overview are given as well as how many transport authorities mentioned these practices. For this report a selection of these practices was made.

Table 4.1: Practices mentioned by the Dutch regional transport authorities (Rosdorff, 2021).

Practice	**Number of mentions**
Mobility hubs	8
Zero-emission buses	6
Chain mobility	6
Demand responsive transport	5
Mobility-as-a-Service	5
Straightening lines	4
Bicycle as access mode	4
Bicycle sharing	4
Park-and-rides	4
“Buurtbussen” (Neighbourhood buses)	4
Car sharing	1

Chain mobility and mobility-as-a-service (MaaS) focus on offering a multimodal transport service from door to door by combining multiple mode choices in the planning process of individual trips (MaaS Alliance, 2017). Both can be seen as combinations of multiple practices such as bicycle sharing and demand responsive transport (DRT), which are also mentioned as individual practices. Therefore, chain mobility and MaaS were not included in this report. Car sharing was also not included, because it was only mentioned once as an example of shared mobility. Park-and-rides (P+R) were also only mentioned in combination with mobility hubs. P+R was only included in the section of mobility hubs. The use of zero-emission (ZE) buses did not fit with either the patronage or the coverage function of

Walker (2008). The effects of ZE buses on the network design will become very small, as is discussed in Appendix A. Currently, many ZE buses have a limited range before they have to be charged. In the near future, ZE buses will have a range close to the maximum of current daily operations, which allows them to be used similarly to current diesel buses. Until that moment, the introduction of ZE buses is eased when buses can drive shorter distances. Finally, the "Buurtbussen"[5] were also excluded. Buurtbussen are 40 percent cheaper than regular bus services (CROW, 2016) and simpler in use than DRT (ROVER, 2020), but there are ethical concerns with the replacement of services with paid drivers by similar service with volunteers (Jacobs, 2020; Pieper et al., 2014). These ethical concerns were the reason buurtbussen were not included in this report. The remaining practices were split in groups affecting either the patronage or the coverage goals. Table 4.2 shows the practices of Table 4.1 that remained and were looked further into in this report.

Table 4.2: Practices included in this report.

Patronage practices	Coverage practices
Mobility hubs	Demand responsive transport
Straightening lines	Bicycle as access mode
	Bicycle sharing

4.1.1. Patronage Practices

Mobility Hubs

Mobility hubs are places where multiple modes and services come together. Most authorities mention the use of hubs at fast and frequent public transport stops, where a smooth transfer is provided between high level services and local services (i.e. local bus services, bicycle sharing and DRT services). Transfers are accommodated between public transport and private modes such as bicycles and cars by offering for example bicycle parking and P+R facilities. In the concession of Groningen-Drenthe hubs are already used. All of these hubs include at least bicycle parking and a DRT service, which offers a direct service from the front door to the nearest hub for those that cannot access the hub by other means. A small number of hubs also offer bicycle sharing services or P+R facilities. Many hubs also offer other services, such as Wi-Fi, toilets, and water fountains, to improve the waiting experience. Mobility hubs function as a central location for different mobility services, which is easy to understand for passengers. A legible and coordinated network attracts more passengers (McLeod et al., 2017). Furthermore, making transfers easier and more pleasant fits with the principle of "embracing and managing transfers" of McLeod et al. (2017), which focusses on the patronage goals.

Straightening of Lines

Straightening a bus line means reducing the number of detours and stops in order to decrease the driving time. In essence is this principle a change in approaching the first public transport network design dilemma of stop density, which is given in Figure 4.1. Originally, the view of this dilemma was to have a high stop density to provide easy access for everyone. However, the general public accepts a longer distance to the stop in order to have a faster ride (KiM, 2018). With shorter driving times, the frequency of the service can also be increased, which reduces waiting times and attracts many passengers. For the network design, this means that many lines take a direct route instead of covering every corner of each village and neighbourhood.

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[5] "Buurtbussen", or literally translated as Neighbourhood buses, are bus services with a fixed line operated with small vehicles and volunteers as drivers. These services are usually introduced by citizens' initiatives when a regular bus services is discontinued.

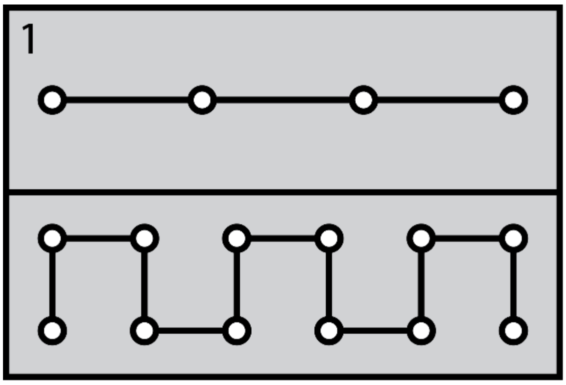

Figure 4.1: Design dilemma one, trade-off between access time and in-vehicle time.

Appendix B describes two real world examples of this trade-off. Two sets of two lines were compared with each set containing one line with many stops and detours and one direct line with fewer stops. In both cases, the direct line has a much lower driving time. In one case, the direct line attracts many more passengers than the slower service. In the other case, this effect is limited, likely because the slower line serves many tourist and leisure destinations. For non-tourist passengers, indications exist that the direct and faster service is much more attractive. According to contact with both the province of Zuid-Holland and Arriva[6], this practice already showed its potential in the past when a bus line that ran through the centre of Zoeterwoude-Dorp was moved to a large road outside of the village. The new service resulted in a large increase in the number of passengers while an alternative parallel route that was introduced in order to serve the centre of the village was discontinued very quickly because of the extremely low passenger numbers.

Reducing the number of stops and straightening the lines is not something new. Assuming only walking as access and egress mode, increasing the existing distances between stops to 600 meter is more optimal and results in faster driving times without losing passengers (Egeter, 1993; Van Nes, 2002). More recently studies have been performed to find acceptable distances to access or egress the bus stop. Van der Blij et al. (2010) stated an area of influence of 450 metres for conventional bus services. For high quality services, with shorter driving times and higher frequencies, the area of influence increased to 800 metres. Brand et al. (2017) assumed the same study area and found a median walking distance of 600 metres to and from conventional bus stops. Furthermore, 75 percent of the trips had a feeder distance of less than 950 metres. For high quality bus services, these distances increased to 750 metres and 1000 metres respectively. Rijsman et al. (2019) concluded much shorter distances of 380 metres and 500 metres respectively for tram services. The difference between the distances of Rijsman et al. (2019) and those of Brand et al. (2017) might be explained by the high stop density of the tram stops, reducing the incentives to walk any further than the revealed distances.

4.1.2. Coverage Practices

Demand Responsive Transport

Originally, demand responsive transport (DRT) consisted of shared taxis and dial-a-ride bus services as an added service on top of the existing public transport services (Mageean & Nelson, 2003). Many of these services focussed on people who cannot use regular public transport services. In recent years, a trend in the Netherlands emerged to convert low frequent, little used, conventional bus lines to flexible DRT services (ROVER, 2020). This trend allows the potential coverage of the PT system as a whole to be increased. In Table 4.3 a small overview of already existing DRT services in the Netherlands is given. DRT services can be mostly divided in two groups: door-to-door and stop-to-stop.

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[6] Arriva was the transport operator of the case study area during the writing of this report

Table 4.3: Overview of DRT systems in the Netherlands.

Name	**Location of service**	**Type of service**	**Minimum reservation time (in minutes)**
Maasvlaktehopper	Maasvlakte	Stop-to-stop	30*
BeachHub Hopper	Schouwen-Duiveland beach	Stop-to-stop	60
Hubtaxi	Groningen & Drenthe	Door-to-hub	60
Deur-halte taxi	Southern Zuid-Holland	Door-to-stop	60
Mokumflex	Rural Amsterdam	Stop-to-stop	45
Overal Flex	Noord-Holland Noord	Stop-to-station	30
SyntusFlex	Woerden, Mijdrecht & Wilnis	Stop-to-stop	30**
Delfthopper	Delft	Stop-to-stop	30
AML Flex	Amstelveen, Uithoorn & Haarlemmermeer	Stop-to-stop	30
Texelhopper	Texel	Stop-to-stop	30
U-Flex	Utrecht, Houten, Maarssen & More	Stop-to-stop	30
Vlinder	Mainly Doetinchem, Lochem, Venlo & Zaltbommel	Stop-to-stop	60***
Regiotaxi	Multiple	Door-to-door	60

* During weekdays, 60 minutes in the evenings and weekends
** 30 minutes before planned arrival at the destination instead of start of the trip
*** For trips starting at a train station no reservation has to be made

Door-to-door (and door-to-stop) DRT focuses primarily on passengers that cannot use the regular public transport services. Most of the new converted services are stop-to-stop DRT and focus on keeping areas where a regular bus service is not viable, connected. Stop-to-stop services can be direct service any two stops in the service area or connected via a larger centralized hub where transfers to other public transport services can be made. In the latter, direct trips between two stops are not always possible. For passengers a switch from a regular service to a DRT service is usually a downgrade, because reservations must be made. Some existing DRT services, such as the Vlinder services, have a vehicle standing at a larger hub or train station waiting for passengers. When alighting at such a station reservations are not required which increases the ease of use. Currently, reservations can often only be made by calling the transport operator or by using an app specific for only one service. The improving communication technology allows the process of making reservations to become easier in the future. DRT could also benefit from the trend of automation as one of the most expensive components in DRT systems is the driver.

Although the operation costs of DRT are likely lower than those of fixed line services (Coutinho et al. 2020), data on the exact costs is not publicly available. However, a few case studies have reported the number of vehicles for different DRT services, as well as the number of stops that were served. When combined, these numbers give an indication of how many vehicles are required at any given moment for the number of stops in the service. Table 4.4 gives these numbers for the aforementioned case studies. Both Dutch cases (Amsterdam and Nijmegen) seem to require one vehicle per approximately 25 stops. For the case in Helsinki, this number was significantly different in both the realized and the planned case. The planned situation was never reached, so it is unclear how realistic the number of stops per vehicle was. In the realized case the DRT service was introduced as an add-on for the existing PT system, whereas in the Dutch cases the DRT service was introduced as a replacement for discontinued fixed line services. This might explain the difference in number of stops per vehicle.

Table 4.4: Stops per vehicle for other demand responsive services.

Region	Service	# stops	# vehicles	Stops per vehicle	Source
Amsterdam rural north	Mokumflex	45	2	23	(Coutinho et al., 2020)
Nijmegen	Breng flex	255	9	28	(Alonso-González et al., 2018)
Helsinki	Kutsuplus (realized)	≈ 1000	15	67	(Jokinen et al., 2019)
Helsinki	Kutsuplus (planned)	≈ 1000	100	10	(Jokinen et al., 2019)

Bicycles as Access Mode

The combination of bicycle and public transport shows great potential (Martens, 2007; Kager et al., 2016; Brand et al., 2017; Shelat et al., 2018). Currently, many stops are fitted with bicycle parking facilities. However, the network itself is not built with the intention of using bicycles as a feeder mode. This can be seen by the distance between stops, which is often around 400 metres or less, even for longer regional lines, with exceptions for the R-Net lines which have longer stop distances. The bicycle starts to become an acceptable access mode with a frequency of at least four times per hour (KiM, 2018). When bicycles are an acceptable feeder mode, the access distance is allowed to be greater. Table 4.5 shows the areas of influence for regular bus services and high quality services with different levels of cycling as access mode according to Van der Blij et al. (2010). As can be seen in this table, the distance becomes larger when cycling is more considered as access mode. Table 4.6 shows both the median access distances and the maximum access distance of 75 percent of passengers for different services using different modes. By allowing these longer access distances, the stop density can be decreased without losing the coverage function, as long as adequate bicycle parking facilities are provided. An exception exists for the 6 percent of the Dutch population who are physically not able to cover these distances, neither by walking nor cycling (KiM, 2018). The mobility of these people might be reduced by increasing the access distances. However, the existing stop distance of 400 metres is already too far for most people in this group (Egeter, 1993). An alternative service should be available for this group.

Table 4.5: Areas of influence of different levels of service and different access modes (Van der Blij et al., 2010).

	Area of Influence (in metres)
Regular Services	450
High Quality Services (only walking)	800
High Quality Services (walking and cycling)	1150
High Quality Services (only cycling)	2350

Table 4.6: Walking and cycling access distances for different services.

	Walking Access (in metres)		Bicycle Access (in metres)	
	Median	75% of passengers	Median	75% of passengers
Brand et al. (2017) Regular Services	600	950	600	1250
Brand et al. (2017) High Quality Services	750	1000	1100	1750
Rijsman et al. (2019) Tram Services	380	500	1025	1400

Bicycle Sharing

While using a bicycle as access mode was already an option for most Dutch people, the use of cycling as egress mode was often not an option. For some trips a private bike at the activity end is possible, but for most trips this is too unattractive or simply impossible. A rapid growth of different bicycle sharing schemes solves this problem by offering a bicycle at the egress side of the PT trip (Oeschger et al., 2020). The existing trend of sharification makes the use of shared bicycles also more accepted. Shared bicycles are most likely to be used by infrequent PT travellers (Van Kuijk et al., 2021), because frequent travellers are generally more reluctant to changing their existing habits. There are also indication that shared modes are more likely used in structural PT trips, where the shared bicycle competes with a second private bicycle (Martens, 2007). Contrarily, travellers that already have a private bicycle at the activity end are less likely to use a shared bicycle (Van Kuijk et al., 2021), because private bicycles are often cheaper. The costs of an "OV-fiets"[7] are, as of 2021, €3,95 per day (NS, n.d.). A private bicycle is often cheaper than the daily use of an "OV-fiets". Ma et al. (2020) compared the characteristics of three different types of bicycle sharing schemes in the Netherlands, including the "OV-fiets". The findings shows that few "OV-fiets" commuters replaced their private bicycle for a shared bicycle, because of the high price of the "OV-fiets".

According to Ma et al. (2020), many shared bicycle users started using the bus and tram less, indicating that shared bicycles also provide an alternative for local services. On the other hand, users of free floating shared bicycles used the bus and tram more, because the possibility of a shared bicycle near the stop made these services more attractive. The train was also increasingly used by shared bicycle users. This shows that shared bicycles compliment both train and bus services. Van Kuijk et al. (2021) also found that shared bicycles have an opportunity as an egress mode at local stops. It was also stated that these bicycles should not be offered at every stop, as that would leave many bicycles unused at smaller stops. A centralized approach by offering the bicycles at larger stops and transfer hubs is more fitting with the demand. Nevertheless, the availability of shared bicycles allows for greater egress distances similar to how the use of private bicycles allows for greater access distances.

4.1.3. Conclusions

Based on these practices, the future network is based mostly on straight and frequent lines connecting multiple mobility hubs on their routes. At these mobility hubs, interchanges between different mobility services are possible. Access to the stops of these lines is done not only by walking but also by cycling, requiring a much lower stop density. Egress distances are increased as well at the mobility hubs equipped with bicycle sharing services. Areas with too little demand are connected to the rest of the bus network using DRT services with a high stop density in order to increase the accessibility. When demand is too high for DRT but too low for a high quality service, a regular line is still used, but these lines have a lower stop density than currently is used. Such a regular line connects areas that are too far from a high quality service to one or more hubs. In Figure 4.2, a schematic example is shown of how such a network could look.

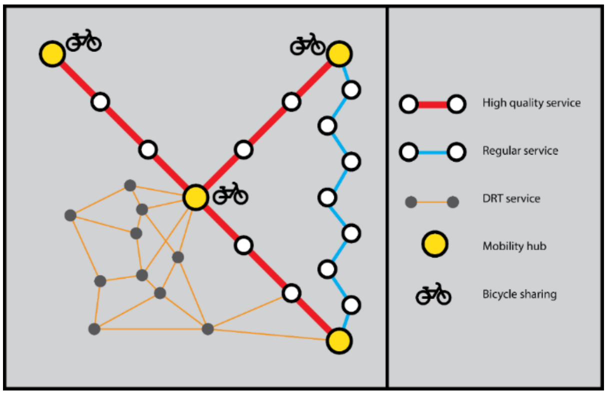

Figure 4.2: Schematic network example with the practices included.

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[7] The "OV-fiets" or PT-bike is the most common shared bicycle in the Netherlands. These bicycles are generally offered at train stations of all sizes, but also at some larger PT hubs.

4.2. Segmentations

Treating all trips the same in a bus network design creates a too large simplification. Trips differ in purpose, traveller, and location with each varying in their characteristics. Therefore, several segmentations were made in order to differentiate between several groups of trip purposes, travellers and locations.

4.2.1. Trip Segmentation

The first segmentation was made for the trip purposes. Traditionally, commuting is the trip purpose with most attention. However, commuting only accounts for a fifth of all trips and a quarter of the total distance (Schwanen et al., 2001). In order to serve a larger proportion of the trips, the focus has to be broadened to more trip purposes. The CBS (2020d) recognizes nine trip purposes: which are:

- Commuting: Trips to and from work. These trips are often taken during the rush hours, resulting in a large peak demand for commuting trips.
- Business: Trips for work purposes, but not to the regular or standard workplace.
- Services: Trips made in order to use services that are offered at that specific location, such as a hairdresser or a general practitioner.
- Shopping: Trips specifically made to buy products at the destination, i.e. trips to a shopping mall or a grocery store.
- Education: Any trip for following education, so to schools but also day-cares. Just like commuting trips for education are also often during rush hours.
- Visiting: Trips for visiting or staying at friends or family.
- Leisure: Any trip to a leisure destination, i.e. restaurants, cafes, sports facilities or any other destination to perform a hobby.
- Touring: Trips made purely for the trip, for example a walk through a park or a cycling roundtrip.
- Other: Any other trip that cannot fit in any of the aforementioned categories. This includes walking to a parking place, picking somebody up and access and egress to public transport.

For this report the “touring” and “other” trip purposes were not relevant. Touring trips lack a destination and focus is on the use of the transport mode itself. The “other” trip purpose consists mostly of access and egress between mode. The remaining trip purposes were much more relevant for this research. The frequency and distance of each trip vary over these trip purposes. Figure 4.3 shows this variance of frequency both in general and for trips with a distance between 3,7 kilometres and 50 kilometres as these distances are most relevant for bus transportation (CBS, 2020e). Shorter trips are faster and easier by bike whereas longer trips are faster by train. For these distances commuting is the most common trip purpose, with leisure being second, as can be seen in Figure 4.3. Shopping is much less common for these distances than overall, because many of these trips are shorter than 3,7 kilometre. However, as the third most common trip purpose, there is still a lot of demand for shopping trips. Visiting and education also have significant percentage of these trips. Business and service trips are much less frequent than all other trip purposes.

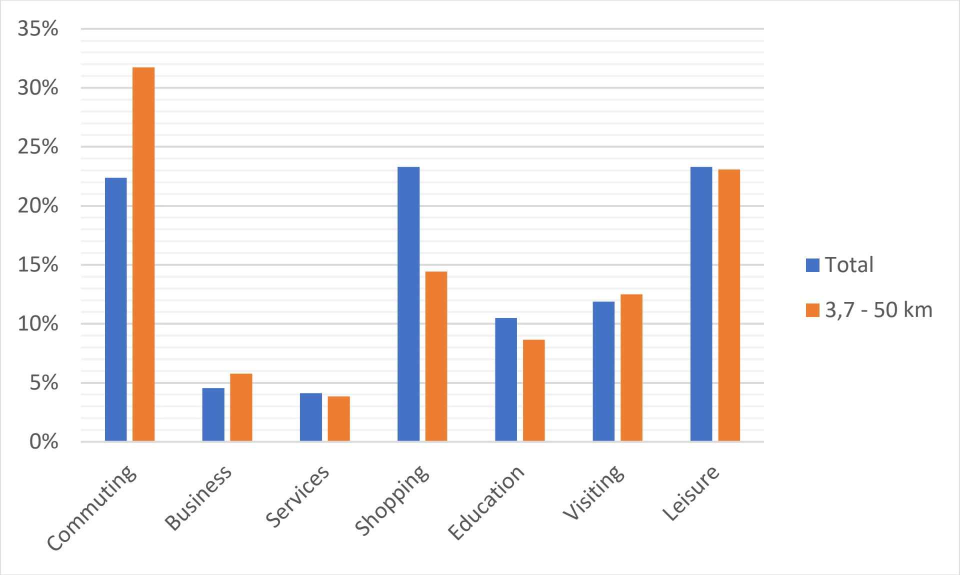

Figure 4.3: Relative frequencies for each trip purpose in Zuid-Holland in 2019 (CBS, 2020d).

4.2.2. Traveller Segmentation

Personal characteristics are related to the travel behaviour, especially in the mode choice and the distances covered (Schwanen et al., 2001). Of the most common characteristics that are usually taken into account, only gender has no relation to age, but differences in travel behaviour between genders are slowly decreasing (Kuhnimhof et al., 2012). For this reason, traveller age was used to create traveller segmentations. In Figure 4.4 the average trip distance and trip frequency per trip purpose is given for several age groups. In the data that was used, foreigners visiting the Netherlands were excluded, meaning that the share of business trips, leisure and shopping could be higher. Figure 4.4 shows that education is the most common trip purpose for school going children education. Between the age 18 and 25 education is also on average the farthest trip purpose. In the working age groups commuting is the most frequent motive and for pensioners this is shopping. Business trips are only performed in the working age and consist of the farthest trips. Outside of business trips, visiting trips are the farthest for most of the age groups. In terms of frequency shopping and leisure are both very common with shopping being more common in older age groups and leisure in younger age groups.

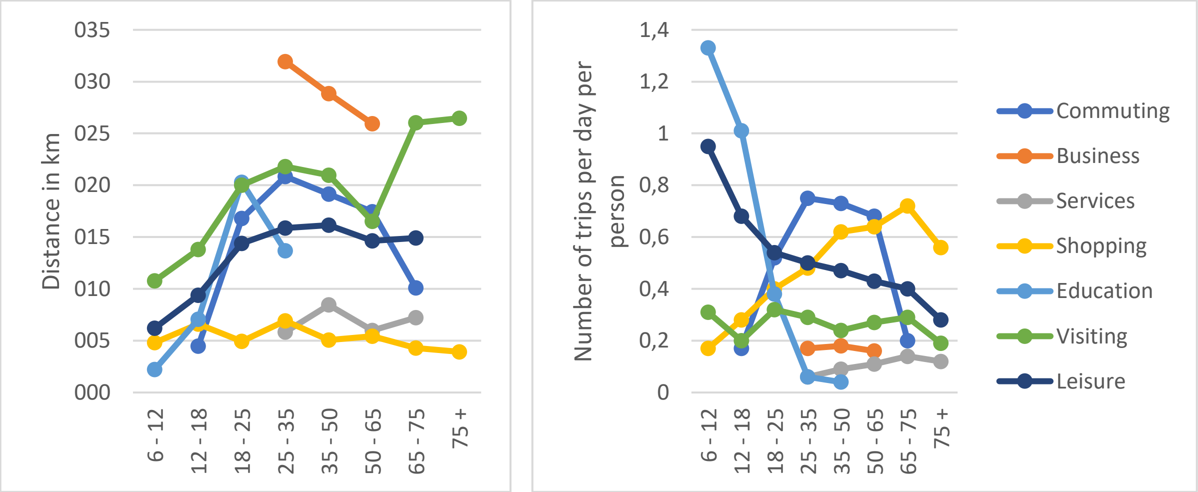

Figure 4.4: Average distance per trip (left) and average trip frequency per person (right) for each age group and each trip purpose in Zuid-Holland in 2019 (CBS, 2020b).

The most important trip purposes for the youngest age groups are education and leisure. Commuting is most important for the working age groups, although leisure and shopping are also significant. Shopping is the most common trip purpose of pensioners. Because education and commuting are overall the trip purposes with the highest frequency, these destinations have to be covered well. Both these trip purposes are mostly common during the rush hours, but outside of the rush hours, leisure and shopping trips also have a high frequency. In order to increase the patronage throughout the day leisure and shopping destinations also have to be served. Visiting is another trip that is relatively frequent throughout all age groups. Because visiting trips are between different homes, it is important to take egress also into account when serving residential areas.

Between the age groups there are also differences in how far people are prepared to travel to and from a bus stop. Travellers under the age of 19 and over the age of 65 walk less far than travellers between the age of 19 and 65 (Daniels & Mulley, 2013). The oldest age group is also overrepresented in the group of mobility impaired people, which consists of 6 percent of the Dutch population (Bakker & Van Hal, 2006). Approximately 66 percent of the mobility impaired people are over 65 years old. This group generally makes fewer trips, except for trips with the service trip purpose. Even less trips are made by PT as paratransit[8] services are more convenient for this group. The trips that are made by PT are generally much farther than for other groups, 44,1 kilometres versus 28,3 kilometres. In order to improve the coverage, it helps to provide a PT services close to the destinations of the "service" trip purpose, such as hospitals, because these destinations have a large societal importance, especially for the people that have a mobility impairment.

4.2.3. Geographic Segmentation

Trip frequencies and distances also differ between urban and rural regions. In rural area most destinations are farther away, reducing the attractiveness for some trip purposes and thus decreasing the frequency. Figure 4.5 shows the trip distance differences for different levels of urbanization[9] and in Figure 4.6 the trip frequencies are shown. In rural regions the frequency of shopping and education trips decreases, likely because the aforementioned increase in distance. Commuting and business trips increase in frequency regardless of the distance. The decrease in frequency of education trips and increase of work-related trips might also indicate a demographic difference, in which the percentage of the working age population is larger in the rural regions and the percentage of the school going population is larger in the urban regions. This difference is not further looked into in this report. Both the frequency and the distances of visiting trips vary, but generally follow the line of the frequency decreasing when the distance increases.

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[8] Paratransit services are door-to-door services similar to a taxi services, but specifically focussed on mobility impaired people. Often these services are heavily subsidized.

[9] The levels of urbanization that were used in this report are the same as those used by the CBS and are based on the number of addresses per square kilometre.

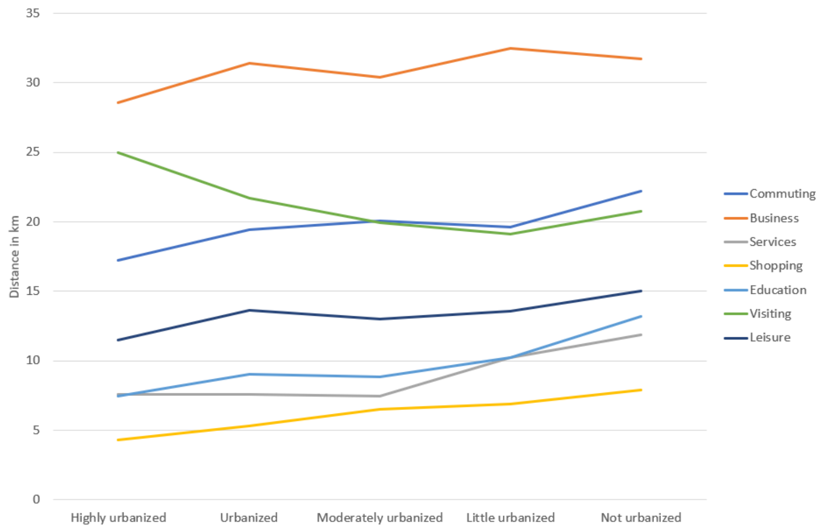

Figure 4.5: Average distance per trip for each level of urbanization for each trip type in 2019 (CBS, 2020d).

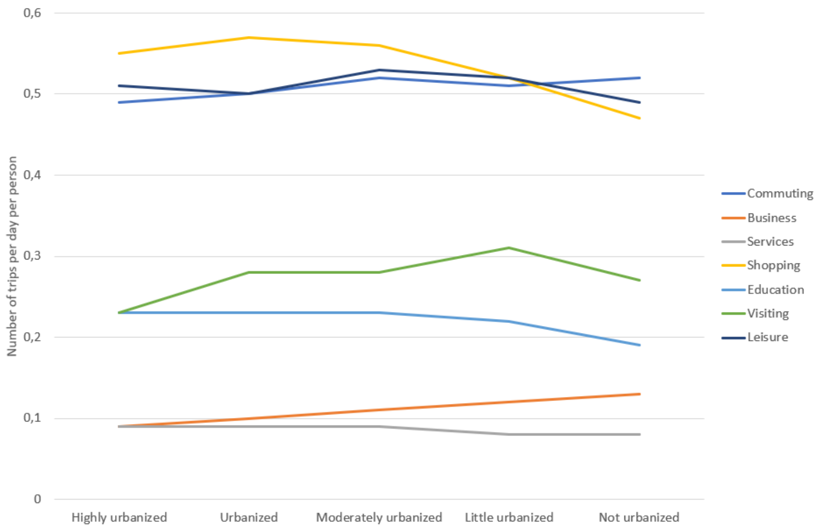

Figure 4.6: Frequency of trips for each level of urbanization for each trip type in 2019 (CBS, 2020d).

Greater trip distances provide an opportunity for the bus if the distance becomes too great to cycle. However, the average cycling distance also increases for more rural regions, as shown in Table 4.7. This indicates a possible willingness to cycle farther, meaning that the catchment areas of rural PT stops might be assumed to be larger when the bicycle is used as access mode. Resulting from the fact that density decreases for less urban areas is that shorter access and egress distances benefit fewer passengers in rural areas than in urban areas, making detours in rural areas more expensive. Therefore, the stop density in rural areas cannot be as high as in urban areas.

Table 4.7: Average distance of a cycling trip for each level of urbanization (CBS, 2020c).

Level of urbanization	**Average distance of a cycling trip (in m)**
Highly urbanized	3790
Urbanized	3830
Moderately urbanized	3940
Little urbanized	4210
Not urbanized	4780

The level of urbanization is not always perfect: some major locations are indicated as not urbanized and the centres of some small cities are seen as highly urbanized. This affects the data that was used. It is likely that when these locations are in a better fitting urban level that the differences between highly urbanized and not urbanized are even larger. However, throughout this report, the same definition of each level was used which makes it good for comparing and combining different data regarding the level of urbanization.

Outside of the urbanisation levels, a segmentation was also made based on the land use areas., which were largely connected to each trip purpose. Because most of the land use areas correspond to the activity end of most trip purposes, the characteristics relevant for the network resulted from the characteristics of the trip purposes. This resulted in the following land use areas that were defined:

- Residential areas: Mostly the home end of a trip, but also an activity end for trips with the visiting trip purpose.
- Shopping centres: Consists of mostly shops, but can also have some services, cafes and restaurants. Shopping is the most obvious trip purpose, but there are also many jobs here making commuting also a common trip purpose. Because of the availability of services and some leisure destinations, these motives can also be found here.
- Office and industrial areas: Usually only the activity end for commuting and business trips.
- Parks and recreational areas: Includes most destinations for leisure, such as parks, sport facilities and more. Mostly for leisure trips, but also some commuting for those that work in these areas.
- Schools: Includes schools from all levels of education. The main destinations of education trips. Also some commuting, mostly by the teacher and other staff, can be found here.
- Hospitals: Large concentrated areas for many services trips. Also includes a lot of commuting by all the staff as well as some visiting trips.

4.2.4. Segmentation Conclusions

The trip segmentation showed that although commuting is a common trip purpose, it is far from the only common trip purpose. For the patronage function, it is important to provide services for other trip purposes as well, because a large part of potential public transport users are not going to or from work. According to the traveller segmentation, the importance of different trip purposes also differs per age group, making the importance of including all different trip purposes even greater. Some of the trip purposes such as shopping and service are more common among the oldest age group which is less likely to cover large distances to and from stops. This makes these trip purposes more important for the coverage function. Differences also exist in the levels of urbanization: for rural regions distances are larger and demand for mobility is more spread out. Short access and egress distance in rural areas is more expensive, but the acceptance of larger cycling distances is slightly higher in rural areas, making it more acceptable to have larger access and egress distances in rural areas. Combining all three segmentations resulted in different characteristics for the land use areas from Section 4.2.3:

- Residential areas are mostly the home end of the majority of trips, access by bicycle is easily done without many services other than parking facilities, increasing the possible access distance. However, visiting is also a common trip purpose. Therefore, egress services also have to be available at the more popular residential area stops, otherwise egress is only possible by walking, resulting in a lower accepted egress distance.

- Shopping centres, especially larger ones, attract a lot of people as shopping is one of the most frequent trip purposes. For pensioners, this is even the most frequent trip purpose. Because this group is less likely to cover a greater egress distance, stops have to be located close to larger shopping centres.

- Office and industrial areas only have commuting and some business trips. Especially commuting trips are frequent and regular, which means that either the stop has to be close by or egress by bicycle has to be stimulated. Egress by bike can be promoted by offering bicycle parking for the option of having a second bike or by offering an attractive bicycle sharing service.

- Parks and recreational areas attract mostly infrequent leisure travellers. These travellers are unlikely to have a personal bicycle at the destination. Therefore, the stop has to be close to the destination or an alternative service has to be available.

- Schools are mostly the destination of students who often have no access to a car. Education trips are similar to commuting trips and thus very frequent and regular. Ideally, larger facilities have good access by public transport for students that live far away. Parking facilities for a second bike or an attractive bicycle sharing service are also possible.

- Hospitals serve as a destination for multiple trip purposes. For the services trip purpose the hospital is an important destination, especially for travellers that cannot walk or cycle far. This means that hospitals have to have a stop very close to the entrance in order to serve these people.

4.3. Hierarchical Levels

One of the design dilemmas, shown in Figure 4.7, states that one of the trade-offs that has to be made is the amount of network levels. A large number of levels results in short travel times on the high levels, but require more transfers. Also, having multiple levels at the same time becomes more expensive to maintain and operate. Both Egeter (1993) and Van Nes (2002) proposed classifications of hierarchical levels. Egeter (1993) made a difference between connecting systems and access systems, as well as a difference between systems within an urban area and systems between urban areas. Connecting systems were defined as systems in which the stop density is a result of minimizing the travel time, whereas in access systems, the stop density is based on access criteria. In Table 4.8, the resulting network levels are given. For this report, the international, national, and interregional systems were not relevant, because in the Netherlands, these systems are usually provided in the form of a train service. For systems between urban areas, the bus fits best for regional connecting and regional access systems.

Table 4.8: Hierarchical levels by Egeter (1993).

	Between urban areas	**Within a single urban area**
Connecting systems	International	
	National	
	Interregional	
	Regional connecting	Urban district
		Agglomeration
Access systems	Regional access	Local access

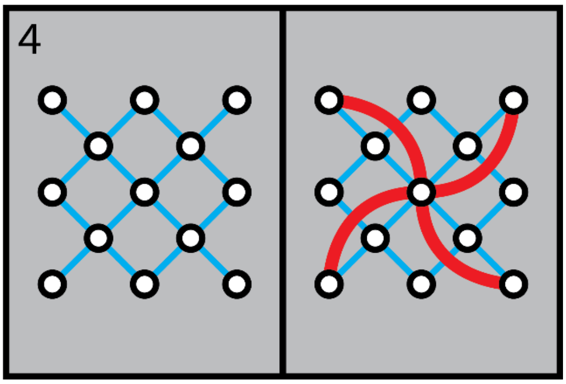

Figure 4.7: Design dilemma of the number of network levels.

Egeter (1993) also introduced micro, meso and macro areas for each system level. A city or village belongs to a different area for each system level. A micro area has, compared to the system level network, a relatively small stop spacing, short travel distance, only one stop and a focus that is almost exclusively external. A meso area has a long stop spacing, short travel distance, only a few stops and a mostly external focus. Finally, a macro area has a large stop spacing, long travel distance, many stops and a mostly internal focus. In Table 4.9, an overview is given for different village and city sizes and what area they belong to in each system level.

Table 4.9: Areas for different city sizes for each system level (Egeter, 1993).

	Connecting Systems				**Access systems**
Number of inhabitants	**National**	**Interregional**	**Regional**	**Agglomeration**	
> 500.000	Micro	Meso	Macro	Macro	Macro
> 75.000		Micro	Meso	Macro	Macro
> 10.000			Micro		Macro
< 10.000					Meso

Van Nes (2002) also differentiated between urban and interurban networks, with three different levels of urban systems and five different levels of interurban systems. In Table 4.10, these levels are given. The interurban levels of Van Nes (2002) are very similar to the connecting systems of Egeter (1993). Only the local, urban and express services are not usually offered by a rail service.

Table 4.10: Hierarchical levels by Van Nes (2002).

	Network level	**Spatial level**	**Stop spacing [km]**
Urban systems	Urban	Neighbourhood	0,6
	Express services	Districts	2
	Agglomeration services	‘City’	6
Interurban systems	Local	Village	3
	Regional	Town	10
	Interregional	City	30
	National	Agglomeration	100
	International	Metropolis	300

For this report, the networks mostly used the local interurban and express service level of Van Nes (2002) as these levels fitted best with the size of the case study. These levels correspond with the straight high quality lines from the practices in Section 4.1 and provided the connecting system of Egeter (1993) combined with the train services. The urban service level of Van Nes (2002) was used for the other lines in the network, creating the access system of Egeter (1993). The stop spacings were adjusted based on the micro, meso and macro areas.

4.4. Conclusions

The combination of the emerging practices, segmentations and hierarchical levels resulted in a design philosophy consisting of two levels of fixed services and one flexible service, as shown in Figure 4.8. The highest level of fixed service is a high quality service with a large stop spacing similar to the express and local interurban services of Van Nes (2002). This service consists of straight lines connecting multiple mobility hubs where connections are made with the lower service levels as well as bicycle sharing and park-and-ride services. The catchment area of the stops of this high quality service depends on the availability of shared bicycles as well as the level of urbanization and the land use around the stops. At the high quality service stops, bicycle parking is available to increase the access catchment area. Destinations such as hospitals have a minimal egress distance due to limitations of the travellers to these destinations.

The second fixed service is comparable to the existing conventional services. This service has a smaller stop spacing comparable to the urban network level of Van Nes (2002). Frequencies are not required to be as high as that of the first service level. However, as a result from this, the catchment area is smaller and the bicycle has a small role as an access mode. This level is most suitable for areas where the demand is too low for a high quality service but too high for a flexible service. More urban regions are mostly served with this service in order to be connected to the mobility hubs.

Finally, there is a flexible service consisting of a demand responsive transport (DRT) service with a very small stop spacing in order to provide accessibility to most homes and destinations that are not served by the fixed services. Many smaller stops are connected to one or more mobility hubs by this service. DRT serves the rural areas where demand is too low for a fixed service. However, it is also used in urban areas that do not fit well with one of the fixed services and have too little demand for an extra fixed service. For ease of use, it is best to have the DRT services centre around one or multiple hubs where the DRT can be accessed.

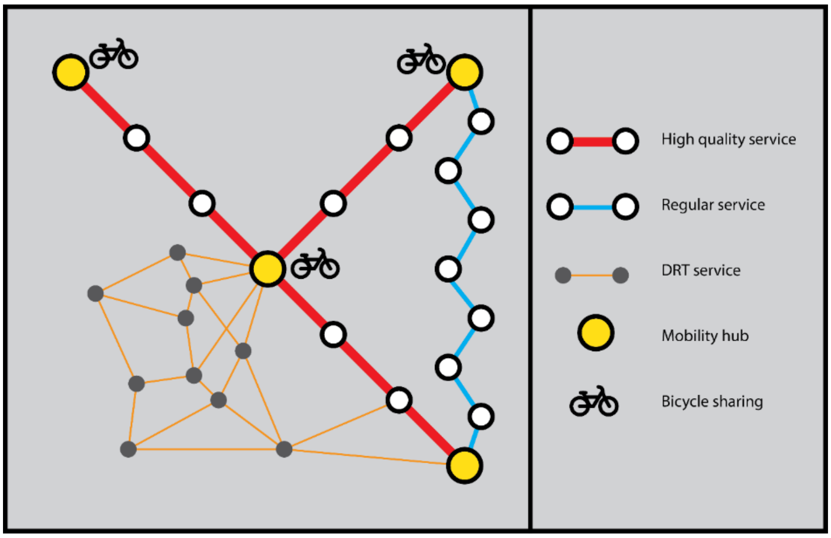

Figure 4.8: Schematic view of the services in the design philosophy.

5. Objectives & Criteria

The foundation of the bus networks was the high quality services which fulfilled the patronage function. The other services were introduced in order to enhance the coverage function. The networks were designed for the patronage function while constraint by the coverage functionalities, leading to the objective, which is presented in Section 5.1, being patronage based. The coverage function was fulfilled by adding criteria to the patronage network. These criteria were grouped in criteria regarding the network as a whole, which are introduced in Section 5.2, and criteria that follow the design philosophy, which are presented and discussed in Section 5.3. Finally in Section 5.4, an overview of the objective and the criteria is given.

5.1. Objectives

In Chapter 1 two patronage goals were given. For transport authorities, the goal was to offer a PT network that competes with cars in an attempt to reduce road congestion and the necessity to expand the space-demanding road network. The number of PT users has to be as high as possible for trips that are otherwise predominantly made by car. For operators the goal was to minimize the cost per timetable hour in order to increase the cost-efficiency of the network. This is achieved when buses drive as full as possible, requiring either more passengers or passengers sitting for a greater distance in the bus. In both cases, the number of passengers have to be as high as possible or the passenger kilometres have to be maximized.

During the initial design, it is difficult to predict the actual number of passengers or passenger kilometres, because there are many different interactions. Therefore, the focus of the initial design is to maximize the total number of trips potentially served by public transport, including train trips because all the different public transport network levels complement each other and create a single network. As a result of this focus, lines were mostly drawn between locations with a large number of trips between them. During the evaluation of the networks, estimations for the total number of passengers and passenger kilometres were made in order to compare the different network designs on these objectives.

5.2. General Criteria

The network as a whole was constraint by two criteria: the maximum and minimum service. There is a limitation to the buses and drivers that can be deployed and therefore a maximum amount of service that can be provided. The maximum service is presented as a maximum number of timetable hours, which is discussed in Section 5.2.1. A minimum of service also has to be provided, otherwise only profitable routes are served, which would degrade the coverage function. In Section 5.2.2 a minimum service is proposed which consists of a percentages of inhabitants and destinations that have to be served.

5.2.1. Maximum Amount of Timetable Hours

An indicator for the service that is provided, is the number of timetable hours (TTH). The number of TTH indicates how many hours the buses are operated and available for passengers. It is an indicator for the service of the complete network. More TTH are beneficial for passengers, but also result in higher operating costs. In the design process and maximum has to be considered in order to avoid the number of TTH to become unrealistically high. In this report, a fixed number of TTH was considered, which was equal to the average daily number of TTH in 2019. In reality, this number is not fixed but dependent on the revenues of the operator. Currently, 35 percent of the operator revenues come directly from ticket sales (Provincie Zuid-Holland, 2021). By attracting more passengers, the number of TTH can be increased. However, incorporating this effect requires many more calculations which would have been too complicated for this report. During the evaluation of the networks, this effect has to be taken into account when drawing conclusions. Furthermore, it was assumed that the TTH of each line comes with the same costs. However, differences can occur because of the use of different vehicles for example. The main hourly operating costs of a bus consist of the driver, which limits the effect of operating different vehicles.

5.2.2. Minimum Services

In the existing criteria, the service minimum depends on the size of the town that is served. Focus is mostly on home addresses, but often destinations are ignored. For the concession of ZHN (Provincie Zuid-Holland, 2020a), the current criteria are:

- For towns of less than 800 inhabitants:
    - Minimum of a door-to-stop DRT service
- For towns between 800 and 3000 inhabitants:
    - At least one stop within 800 metres from the geographic centre and a minimum frequency of 6 times a day for weekdays, 5 times on Saturdays and 4 times on Sundays
- For towns and cities larger than 3000 inhabitants:
    - 80 percent of the home addresses have to be within 500 metres from a stop or 800 metres if it is a stop of a high quality or train service and 100 percent of the home addresses have to be within 800 metres from a stop or 1200 metres for high quality or train services. Minimum frequencies are 12 times a day for weekdays, 9 times on Saturdays and 6 times on Sundays.
- For business districts with more than 2500 jobs:
    - A minimum frequency of 3 times a day for weekdays.

Based on these existing criteria, a simplified set of minimum service criteria was made. This simplification did not differentiate between the size of towns, but requires a minimal percentage of both inhabitants and destinations that have to be served per service level. Of the inhabitants and destinations, 80 percent has to be served by a high quality service. For this criterium, 80 percent was chosen based on the existing criteria that state that 80 percent of the addresses have to be within 500 (or 800, depending on the service level) metres from a stop. In both the existing and in the new criteria, 80 percent has to have a “good” access to the network, although if realistically achievable, it is preferable to have this percentage as high as possible. The remaining inhabitants and destinations have to be served by either a regular or DRT service. In the existing criteria, this results in 100 percent that has to be served. However, these criteria do not take the homes and destinations outside of the larger towns and cities into account. In many cases, the homes and destinations are too rural to serve realistically. Therefore, a choice was made to reduce this percentage to 95 percent of all home and destinations that have to be served by any form of PT. This choice affected the outcome of the network designs: a higher percentage would have resulted in more stops and a more complicated network, but also in a larger number of inhabitants and destinations with access to PT.

5.3. Criteria Resulting from the Design Philosophy

In the design philosophy in Chapter 4 three different service levels were defined: the high quality service, the regular service and the DRT service. Each of these service levels have specific criteria regarding the minimum frequency and the maximum access and egress distances. There were no criteria stating any minimal amount of passengers required for each service level, because the high quality level is used as the standard.

5.3.1. High Quality Service

Minimum Frequency

The high quality service plays a similar role as the current R-Net services. Therefore, the frequency criteria have to be similar to those of the R-Net services, which are given in Table 5.1. In this report a fixed frequency throughout the day was used in order to keep calculations and estimations simple. During the evaluation of passenger numbers, this resulted in an underestimation of rush hour trips and an overestimation of evening and weekend trips. A high quality bus service usually has a frequency of minimally six times per hour (American Public Transportation Association, 2010; Van der Goot, 2010). Seeing as most existing conventional services have a frequency of only once or twice per hour, it was regarded that not enough TTH would be available to offer a frequency of six times per hour for the new high quality services. Of the existing R-Net services, only two lines achieve an average frequency of over 6 times per hour and many do not reach an average frequency of 4 times per hour, as can be seen in Figure 5.1. A more comprehensive table of the frequencies of the existing R-Net services is given in Appendix C. The average is reduced by the lower frequencies during the evenings and the weekends. From these frequencies, it can be stated that an average of four times per hour already give a high quality service in many cases. In a final design which is beyond the scope of this report, the frequencies can be adjusted and detailed in order to fit the demand better over the day and over the different lines.

Table 5.1: Minimal frequency criteria for R-Net (Provincie Zuid-Holland, 2020a).

During which time:	**R-Net criteria**
Rush hours	6
Between rush hours	4
Evenings	2
Saturdays	4
Sundays	2

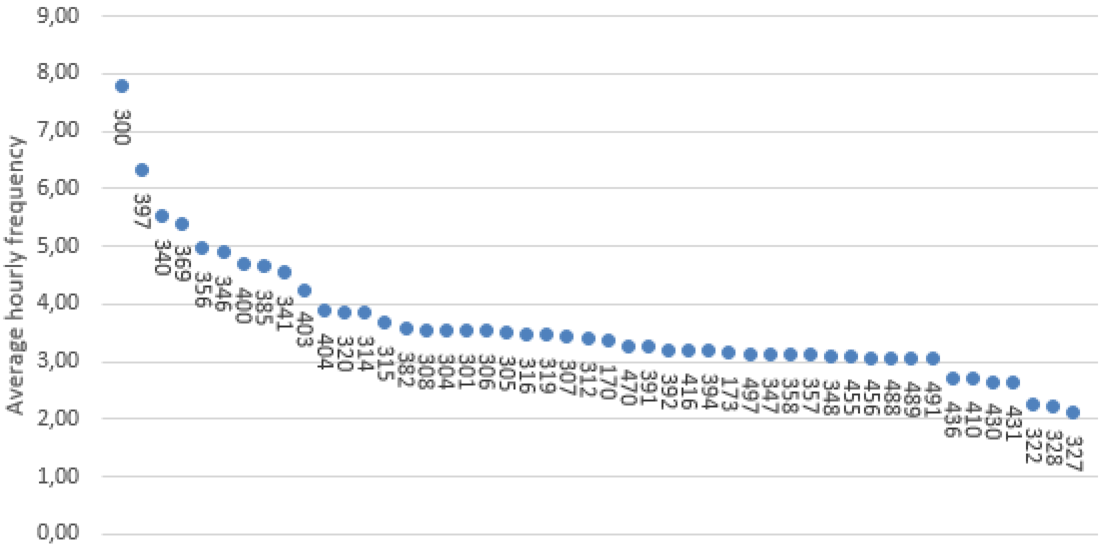

Figure 5.1: Average hourly frequencies of existing R-Net bus services.

Access Distance

Because of the frequency of at least four times per hour, the bicycle becomes accepted as access mode (KiM, 2018). Therefore, the criteria for the access distance were determined based on the bicycle access distances that were found in Van der Blij et al. (2010), Brand et al. (2017), and Rijsman et al. (2019), which were presented in Section 4.1. An estimate was made by using an access distance of

1100 metres, which was the median cycling access distance according to Brand et al. (2017), as a starting point. For each increasingly rural level of urbanization, the access distance was increased by 100 metres, because the number of potential passengers becomes lower and the accepted cycling distance becomes greater for more rural area, as discussed in Section 4.2. The resulting access distances for the high quality service are given in Table 5.2. Even though, these distances are greater than the current criteria for even R-Net services, these distances were considered as conservative, because, according to Brand et al. (2017) and Rijsman et al. (2019), 25 percent of the bicycle passengers travel even further towards their access stop. These distances are also less than the area of influence of Van der Blij et al. (2010) when assuming only cycling.

Table 5.2: Assumed access distances per level of urbanization for high quality bus services.

Level of urbanization	**Access distance (in metres)**
Highly urbanized	1100
Urbanized	1200
Moderately urbanized	1300
Little urbanized	1400
Not urbanized	1500

Egress Distance

Contrary to the access, only walking was assumed as egress mode, unless for stop with bicycle sharing services. Private bicycles at the activity end of the trip were not considered, because these are only an option for a limited number of passengers and specific trip purposes. If bicycle sharing was available, the egress distances were assumed to be the same as the access distances, given in Table 5.2. Otherwise, the egress distances were based on the walking access distances of Van der Blij et al. (2010), Brand et al. (2017), and Rijsman et al. (2019). Again, a conservative approach was taken by using 700 metres as a starting point, which was less than the walking area of influence for high quality services of Van der Blij et al. (2010) and the median walking access distance according to Brand et al. (2017). Because of the lower demand in more rural areas, the egress distance was also assumed to be increased for rural areas, resulting in the distances given in Table 5.3.

Table 5.3: Assumed egress distances per level of urbanization for high quality bus services.

Level of urbanization	**Egress distance by walking (in metres)**	**Egress distance if shared bicycles are available (in metres)**
Highly urbanized	700	1100
Urbanized	750	1200
Moderately urbanized	800	1300
Little urbanized	850	1400
Not urbanized	900	1500

In some cases, the egress distance has to be smaller in order to accommodate the needs of specific travellers. Two cases emerged from the segmentations analysis of Section 4.2: hospitals and shopping centres. Hospitals are an important destination for travellers with a limited mobility. Therefore, it was expected that a large number of passengers to hospitals are not able to walk the same distance as was assumed as acceptable for other destinations. In Appendix D existing services to hospitals were compared in an attempt to find an acceptable egress distance. A maximum acceptable walking distance of 500 metres was assumed, although shorter distances were preferable. If a high quality service is able to serve a hospital, the service has to have a stop within 500 metres walking from the main entrance. For pensioners, who are more likely to have a reduced mobility, shopping is the most frequent trip purpose. Therefore, it is assumed that larger shopping centres also have to have a stop within 500 metres. As mentioned in Section 4.2, shopping centres often function as a destination for several trip purposes, resulting in a large potential for demand. Because of this high demand, the walking time reduction of passengers travelling to these destinations outweighs the increased in-vehicle times of passengers to other destinations.

Criteria in Short

The resulting criteria for the high quality service are given in Table 5.4. The minimum average frequency is four times per hour. If inhabitants live within the given access distance from a stop, these inhabitants were considered as served by the high quality service. The same was true for the destinations, although this was dependent on the availability of shared bikes and whether the destination was a hospital or a shopping centre. If the distance to a stop is larger than given in Table 5.4 the origin or destination was not considered as served. Using these distances, the stop spacing of the local interurban and express urban systems of Van Nes (2002) were achieved especially when taking the micro, meso and macro areas of Egeter (1993) into account which were described in Section 4.3. Compared to the existing criteria mentioned in Section 5.2.2, the access distances were much greater than the R-Net criteria, but the egress distances were similar to the criteria of R-Net unless shared bicycles were available.

Table 5.4: Overview of criteria per level of urbanization for high quality bus services.

		Distances in metres				
Level of urbanization	**Minimum frequency**	**Access**	**Egress by bike**	**Egress by walking**	**Egress to hospitals**	**Egress to shopping areas**
Highly urbanized	4	1100	1100	700	500	500
Urbanized	4	1200	1200	750	500	500
Moderately urbanized	4	1300	1300	800	500	500
Little urbanized	4	1400	1400	850	500	500
Not urbanized	4	1500	1500	900	500	500

5.3.2. Regular Service

Minimum Frequency

The minimum frequency for a regular service did not have to be as high as for the high quality service. However, compared to the DRT service the regular service has to be of a higher quality. According to Table 4.3 in Section 4.1, many stop-to-stop services have a minimum reservation time of 30 minutes. Such service has the same average waiting time as an hourly service, but often with more travel time options. Therefore, a regular service has to have a minimal frequency of twice per hour, resulting in an average waiting time of only 15 minutes.

Access and Egress Distance

Because of the lower frequency of the regular service, cycling is not considered as either access or egress mode. For this service, the access distances of the regular services according to Van der Blij et al. (2010), Brand et al. (2017), and Rijsman et al. (2019), were used instead of the access distances of high quality services. The median walking distances vary between 380 metres as stated in Rijsman et al. (2019) and 600 metres as reported by Brand et al. (2017). The area of influence of Van der Blij et al. (2010) was in between these two with 450 metres, which was also chosen as the base for the access and egress distance in the most urban areas. As can be seen in Table 5.5, the distances were once more increased for less urban areas.

Table 5.5: Feeder distance per level of urbanization for regular bus services.

Level of urbanization	**Feeder distance (in metres)**
Highly urbanized	450
Urbanized	500
Moderately urbanized	550
Little urbanized	600
Not urbanized	650

Similar to the high quality service, hospitals and shopping centres deserved extra attention. According to the findings in Appendix D, an acceptable walking distance to hospitals was approximately 200 metres for a regular service. For shopping centres, this number was too low, because many streets in and around these centres are not accessible for buses. Furthermore, many shopping centres do not have a clear entrance which is the case for hospitals. A requirement of 200 metres would result in too many stops close to each other. Therefore, the acceptable egress distance for most shopping centres by regular services was chosen to be the same 450 metres as for the highly urbanized areas.

Criteria in Short

The criteria for the regular services are shown in Table 5.6. The minimum frequency is twice per hour. The access and egress distances resulted in a slightly larger stop spacing than that of the smallest urban system of Van Nes (2002). However, because of the requirement of serving 95 percent of the inhabitants and destinations, overlaps occur between the service areas of the different stops resulting in a smaller stop spacing in practice. The criteria for the distances were slightly stricter than those of the existing criteria. The reason for this is that the high quality service runs as the backbone of the bus system and serving the patronage function allowing the regular bus service to focus even more on the coverage function.

Table 5.6: Overview of criteria per level of urbanization for regular bus services.

Level of urbanization	**Minimum frequency**	**Distance in metre** **Access**	**Egress**	**Egress to hospitals**	**Egress to shopping areas**
Highly urbanized	2	450	450	200	450
Urbanized	2	500	500	200	450
Moderately urbanized	2	550	550	200	450
Little urbanized	2	600	600	200	450
Not urbanized	2	650	650	200	450

5.3.3. Demand Responsive Service

Although the DRT service does not require a scheduled frequency, the minimum reservation time has to be at most 30 minutes in order to stay in line with most existing stop-to-stop DRT services as can be seen in Table 4.3 in Section 4.1.2. Because the DRT service is focussed mostly towards the travellers that are unable to cover greater access and egress distances, short access and egress distances are required. Also, because of this focus, no differentiation was made between the urbanizations levels in order to bring the stop close to these travellers, regardless of the size of the demand. An access and egress distance of 400 metres was chosen, because this fits well with the existing stop density. This distance has to be a short as possible for stops near hospitals, because these are especially important destinations for this target group. Furthermore as discussed in Section 4.1.2, one vehicle with driver was required to be available per approximately 25 stops from the beginning until the end of the daily operation. The cost in TTH of the DRT service, was assumed to be the length of the service times the number of vehicles required. For example, a DRT service operating 25 stops between 7 AM and 11 PM requires on vehicle for 16 hours. Therefore, the cost of this example service would be 16 TTH.

5.4. Conclusions

The objective was to maximize the number of trips served by the complete PT system in the study area in order to fulfil the patronage goals. The coverage goals were served in the criteria. A maximum of available timetable hours was assumed to be the same as used for the bus services in 2019. A minimum of 80 percent of the inhabitants and destinations have to be served with high quality services. Furthermore, a minimum of 95 percent has to be served by any service (i.e. high quality, regular or DRT). These percentages ensure that all locations were served by public transport, which fits the coverage goals. The high quality service has to have a minimal frequency of 4 times per hour in order to be a high quality service, while a regular service has to have a minimal frequency of 2 times per hour. The access and egress distances for the high quality service can be found in Table 5.4 and those for the regular service in Table 5.6. The DRT service has a minimal reservation time of 30 minutes at most. The access and egress distances of the DRT service were 400 metres for all urbanization levels. For hospitals, the access and egress have to be as close as possible to the main entrance. One demand responsive vehicle can serve around 25 stops.

6. Area Characteristics

The design philosophy and the objectives and criteria from Chapters 4 and 5 were universal for any Dutch case. In this chapter, the focus shifts towards the specific case study as presented in Section 3.1. First in Section 6.1, the demand for mobility is determined and visualized. Then in Section 6.2, the existing supply of mobility is presented.

6.1. Demand Characteristics

Section 3.1 defined the municipalities that made up the main study area, which is shown in Figure 6.1. Table 6.1 gives an impression of the amount of inhabitants and workplaces in each municipality, as well as the main settlements of each municipality. Neighbouring municipalities, such as Haarlem, Haarlemmermeer, Amsterdam, Den Haag and Zoetermeer, have a great influence on the main area, because they have large populations, many job opportunities and services that affect the demand within the main area. Neighbouring aggravated NRM zones up to 5500 metres from the main study area were included in the surrounding study area. This distance was chosen in order to include Schiphol Airport which has a large demand, but without making the area too big for all the calculations.

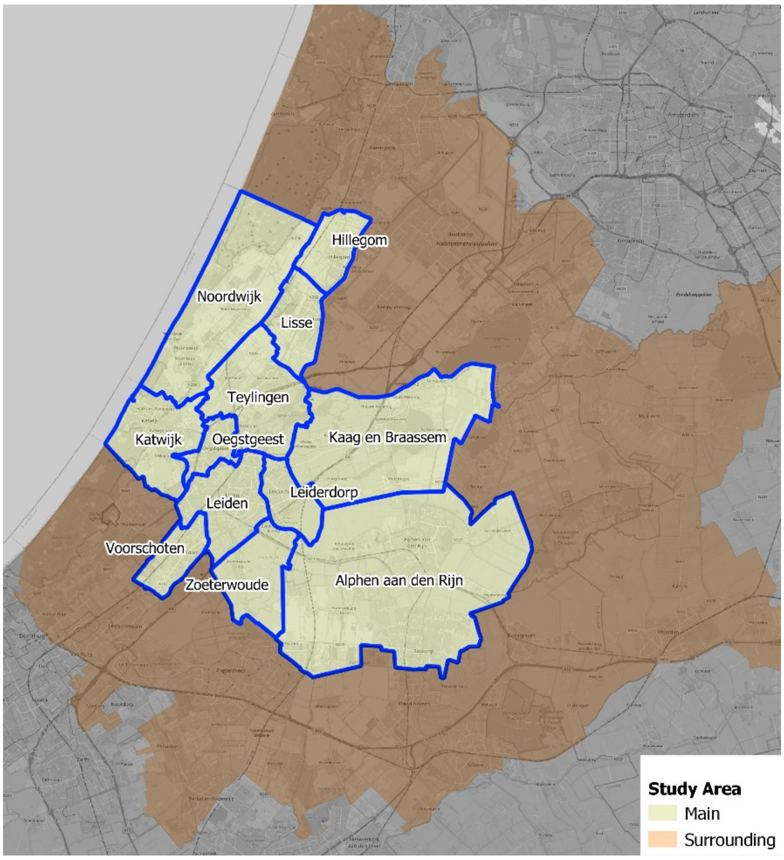

Figure 6.1: The municipalities in the main study area (OpenStreetMap contributors, n.d.; PDOK, 2020).

Table 6.1: Municipalities in the study area with the number of inhabitants, jobs, and the main settlements in 2019 (CBS, 2020g; LISA, n.d.).

Municipality	**Inhabitants**	**Jobs**	**Settlements**
Alphen aan den Rijn	110.986	48.370	Alphen aan den Rijn, Boskoop, Hazerswoude, and more
Hillegom	21.966	7.830	Hillegom
Kaag en Braassem	26.866	10.260	Roelofarendsveen, Leimuiden, Oude Wetering, Woubrugge, and more
Katwijk	65.302	24.330	Katwijk, Rijnsburg, Valkenburg
Leiden	124.899	72.870	Leiden
Leiderdorp	27.109	12.440	Leiderdorp
Lisse	22.800	9.460	Lisse
Noordwijk	42.859	23.690	Noordwijk, Noorwijkerhout, De Zilk
Oegstgeest	24.426	8.070	Oegstgeest
Teylingen	37.061	16.220	Sassenheim, Voorhout, Warmond
Voorschoten	25.479	6.980	Voorschoten
Zoeterwoude	8.450	7.410	Zoeterwoude-Dorp, Zoeterwoude-Rijndijk

In this section, the data and the weight assignment model, as presented in Section 3.2.3, were used in order to create an image of where demand for mobility exists in the study area. The data points of the inhabitants and each destination that were used in the weight assignment model, are visualized in Appendix E. In order to calculate the weights of the inhabitants, age groups and their access distance had to be determined as these were required for Equation 3.2 of the weight assignment model. The age groups were created by combining the age groups available in the CBS "Vierkantstatistieken" and the age groups used in Daniels & Mulley (2013), resulting in three age groups: 24 years old and younger, between 25 and 64 years old, and 65 years old and older. As mentioned in Section 4.2.2, the youngest and oldest age groups generally have a lower access distance. Because the youngest two age groups are generally able to cycle, the access distances for these age groups were chosen based on the access distances of the high quality service, with some difference between the two groups to fit with the findings of Daniels & Mulley (2013). The oldest age group was used as a proxy for the passengers that are unable to cycle. Therefore, the access distance of the regular bus service was chosen for this group. The resulting age groups and their corresponding access distances that were used in Equation 3.2 of the weight assignment model are given in Table 6.2. Furthermore, the share of the total trips of each trip purpose was used for Equation 3.3. of the weight assignment model in order to calculate the importance of each trip purpose. Table 6.3 shows the original share versus the resulting importance of each trip purpose. With these additional inputs, the weights of all data points were calculated.

Table 6.2: The age groups and access distances used in the weight assignment model.

Age group	**Access distance**
0 - 24	1100
25 - 64	1500
65 +	450

Table 6.3: Share of all trips and importance of each trip purpose.

	Commuting	***Business***	***Hospitals***	***City Halls***	***Shopping***	***Education***	***Leisure***	***Visiting***	***Total***
Share of all trips (in %)	31,7	5,8	3,8	3,8	14,4	8,7	23,1	12,5	**103,8**
Importance (in %)	30,54	5,59	3,66	3,66	13,87	8,38	22,25	12,04	**100**

Applying the weight assignment model on the study area and the surrounding zones resulted in a large set of individual points with a given weight. These weight points were projected on a map in order to find all locations with a significant mobility demand. A heatmap of the weight of all these points is shown in Figure 6.2. The largest demand in the main study area was concentrated in the centre of Leiden. In the rest of the main study area, Katwijk and Alphen aan den Rijn also show some large concentrations of demand and smaller pockets of demand are spread throughout the study area in and around the rest of the villages. In the surrounding area, the centres of Haarlem, Den Haag and Zoetermeer also clearly light up. The demand in and around Schiphol and Hoofddorp was likely significantly reduced resulting from the lack of data points for the commuting and business trip purpose.

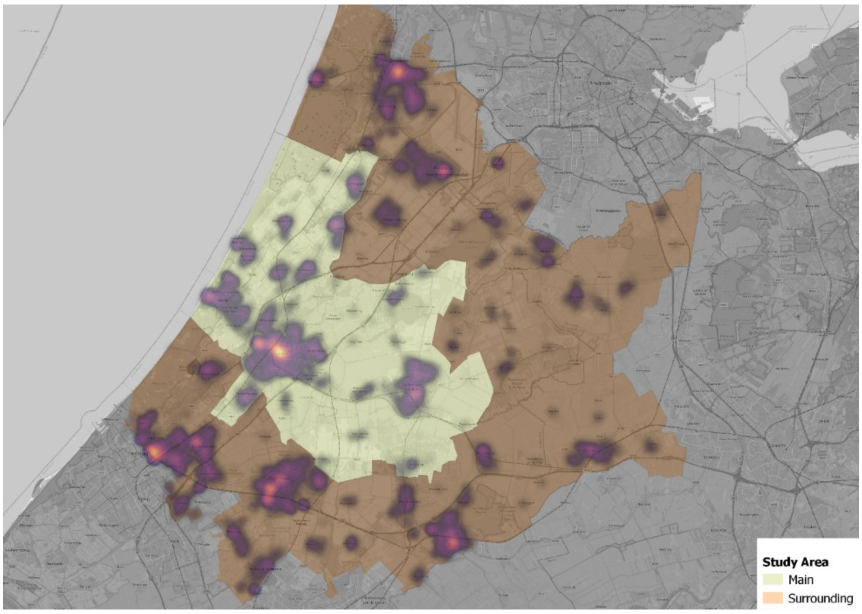

Figure 6.2: Heatmap of the demand based on the weight points (OpenStreetMap contributors, n.d.).

6.2. Supply Characteristics

The supply consisted of the PT services in the main study area of 2019 and the existing (and some planned) high quality bus, tram and metro services in the surrounding area, which are all shown in Figure 6.3. The segments of the services in the surrounding area had to have a minimal highest frequency of four times per hour in order to be included. As a result of this, some tram and R-Net bus services were excluded. As of 2019, only three high quality R-Net bus lines existed in the main study area. At the same time, much of the surrounding area had a more expansive high quality network. Most of the regular lines had a frequency of only once or twice per hour and had many branches and parallel routes. In 2019 on average 1601 TTH per day were used to offer the internal network and the average time between the first and last service of the conventional lines in the study area was 16,39 hours (Arriva, 2018). For R-Net lines in general, this number was 18,64 hours, which was based on the results of Appendix C. The external high quality services already show that lines were more spread out and less branches exist. During the design phase the external high quality services were also included. Connections to these services were made in order to extend the reach of the new services.

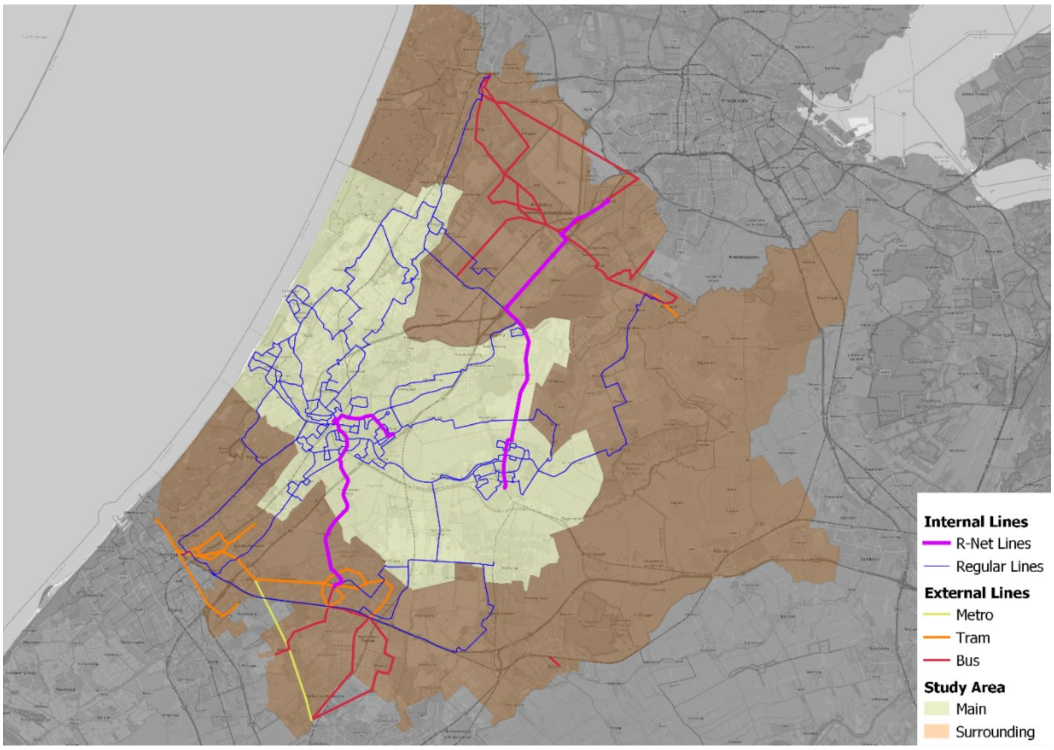

Figure 6.3: Layout of the public transport network in 2019 and high quality services in the surrounding area (OpenStreetMap contributors, n.d.).

The same internal bus network is shown in Figure 6.4 alongside the existing train services, which provide arteries with fast services which complement the bus services. However, several bus lines were run parallel to the train services as if there was a competition between the two. Many lines of the internal network were focussed on Leiden Centraal station even if they started farther from Leiden and had other stations closer by.

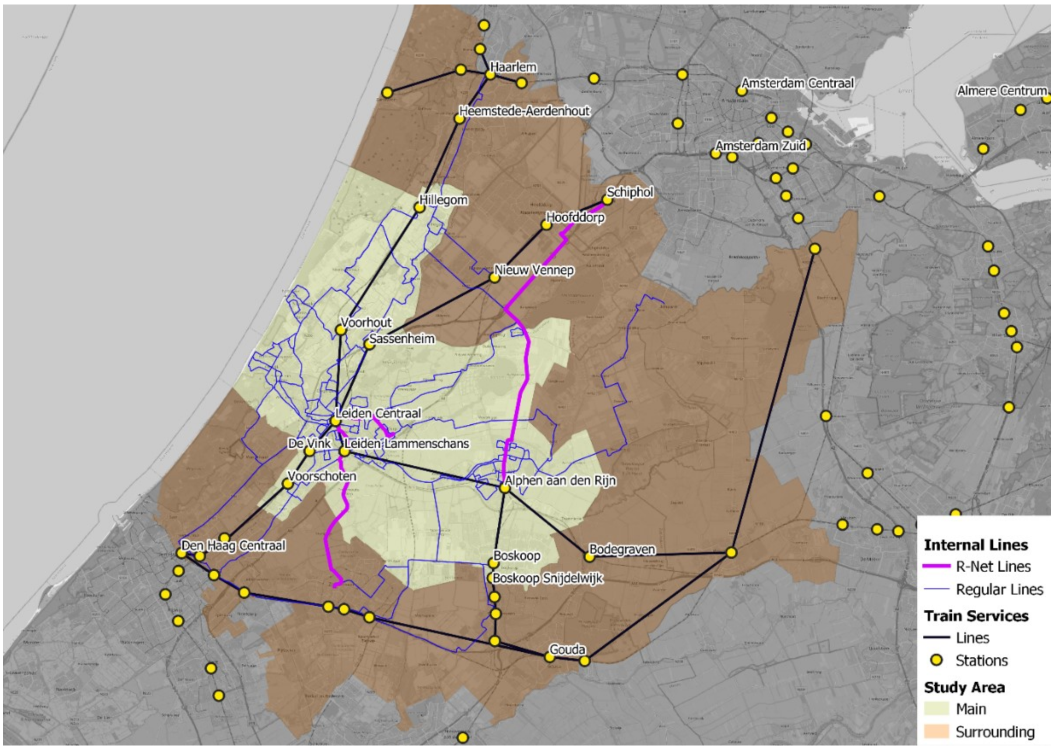

Figure 6.4: Layout of the public transport network in 2019 and all train services in the study area (OpenStreetMap contributors, n.d.).

In 2019 some DRT services existed: two stop-to-stop services operating line services during hours with low demand and a door-to-stop service serving small towns with less than 3.000 inhabitants or outside the boundaries of any town or city. Furthermore, four buurtbussen were operated in the study area. Neither the existing DRT services nor the buurtbussen were included in the 1601 daily available TTH.

Removing all the internal bus lines from the system left only the train services. Figure 6.5 shows the remaining stops in the main study area and the stops of the high quality service in the surrounding area. In the main study area, 10 stations existed of which 7 are equipped with a bicycle sharing scheme, forming the initial supply of PT in the new designs. These stops affect where demand remains in the study area, which is shown in Figure 6.6. In order to find which of the weight points were served by these stops and which were not, the distance of each weight point to the nearest stop was measured. If this distance was within the criteria for the access and egress distances, the weight of the data point was reduced accordingly, similarly to the weight reduction process of the stop location model described in Section 3.2.4. Around the stations with a bicycle sharing scheme, slightly more demand was already served than in the situation without including the effects of shared bicycles.

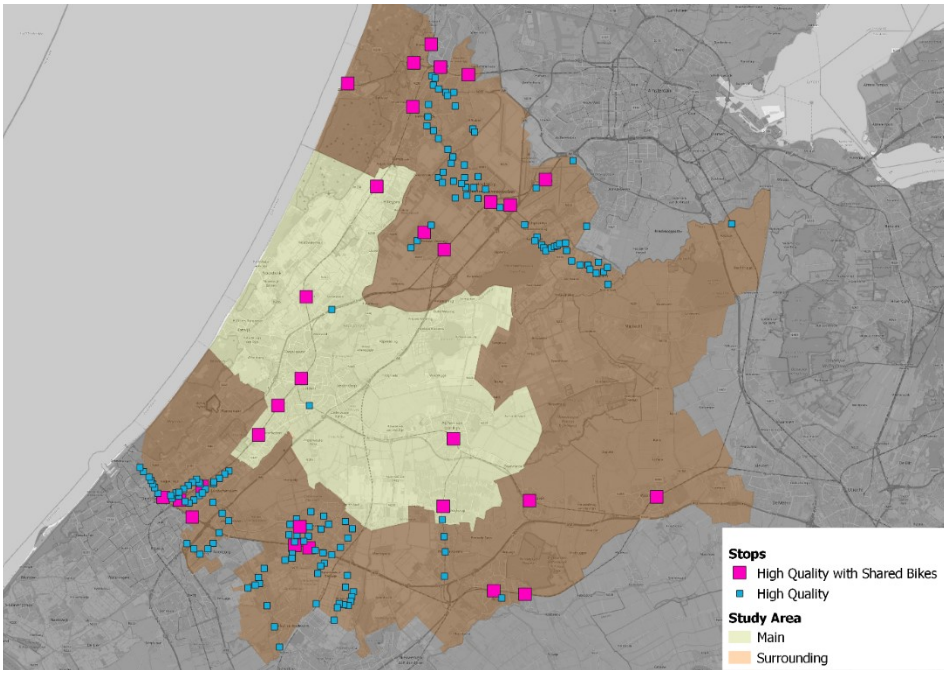

Figure 6.5: Existing high quality stops in the study area (OpenStreetMap contributors, n.d.).

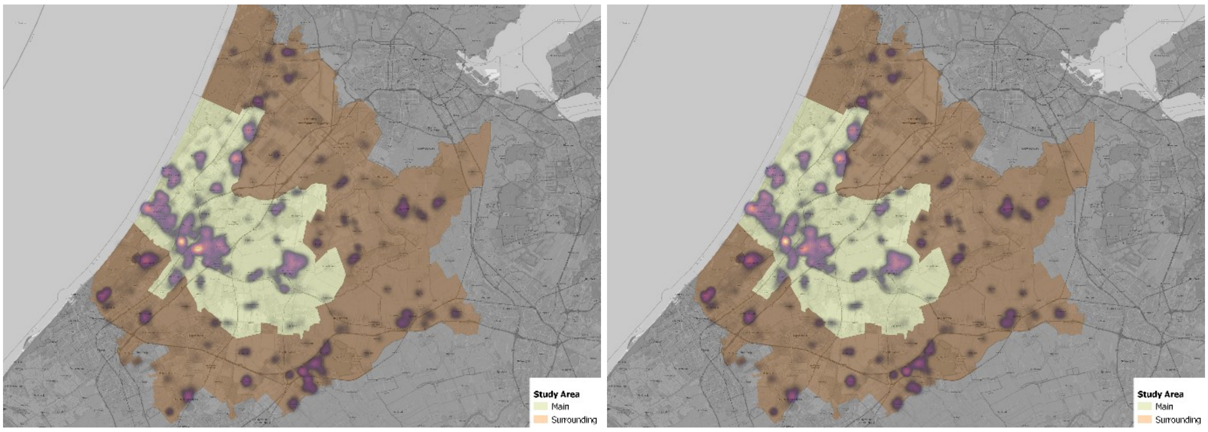

Figure 6.6: Demand after reducing the areas served by existing stops (left: without shared bicycles, right: including bicycle sharing) (OpenStreetMap contributors, n.d.).

6.3. Conclusions

In Figure 6.2 the demand concentrations were given, which was further reduced after determining what demand was already served by higher level PT stops, as can be seen in Figure 6.6. The bus network designs focussed on serving this remaining demand. The starting point for these designs were the initial stops given in Figure 6.5, the train services presented in Figure 6.4, and the bus, tram, and metro services in the surrounding area shown in Figure 6.3. For each network design, a total of 1601 TTH was available to draw the lines in the main study area. Each high quality line in the designs had an average time of 18,64 hours between the first and last service, equal to the average of the existing R-Net services. For the regular lines in the designs, this number was 16,39 hours, equal to the average of the existing regular service in the study area. As mentioned in Section 3.2.4, the DRT service had to have the same time between the first and last possible services as the high quality service.

7. Network Designs

In order to find the effects of combining both patronage and coverage practices, four bus network designs were made, each including different coverage practices which were described in Section 4.1. This way, the effects of each practice is determined while using the same data and design methods. The practice of assuming the bicycle as access mode was included for all network designs, because it also enhances the patronage goals. Each network included different combinations of the DRT service and the bicycle sharing practice: one design including both, one neither, and two design each including either one or the other. These network were designed using the methods presented in Section 3.2.4 which use the results of the area characteristics from Chapter 6. First, the stop locations were determined using the stop location model. Then, lines were drawn between all the resulting stops. In this chapter, the resulting four designs are presented. First, in Section 7.1 the bus network design with neither DRT nor bicycle sharing is presented, followed by the design with DRT but without bicycle sharing in Section 7.2. The network design with bicycle sharing but without DRT is showed in Section 7.3. Finally, the network design that includes both DRT and bicycle sharing is presented in Section 7.4. In this chapter, the four designs are only presented, further evaluations and comparisons were made in Chapter 8.

7.1. Neither DRT nor Bicycle Sharing

The first design used neither the DRT service nor shared bicycles. Figure 7.1 shows the stops required for the high quality and regular services. The number of stops per service in the main study area is given in Table 7.1. Using these stops, the network of Figure 7.2 was created which consists of 10 high quality lines and 7 regular lines. Because in some cases multiple lines were combined into longer lines, some lines seem to be very indirect, resulting in for example line A2 to run in a half loop. Although little demand existed between the ends of the lines according to the NRM data, large demands existed on the straight parts between different sections of the line. The number of TTH that were used to create these lines, is shown in Table 7.2. This number stayed just below the maximum of 1601. Of this number, around 15 percent was used to operate the regular lines.

Table 7.1: Required number of stops within the main study area per service without DRT and bicycle sharing.

Stop type	**Number of stops**
High Quality	93
Regular	43

Table 7.2: Number of timetable hours used per service without DRT and bicycle sharing.

	Timetable hours
High quality	1350
Regular	239
Total	1589

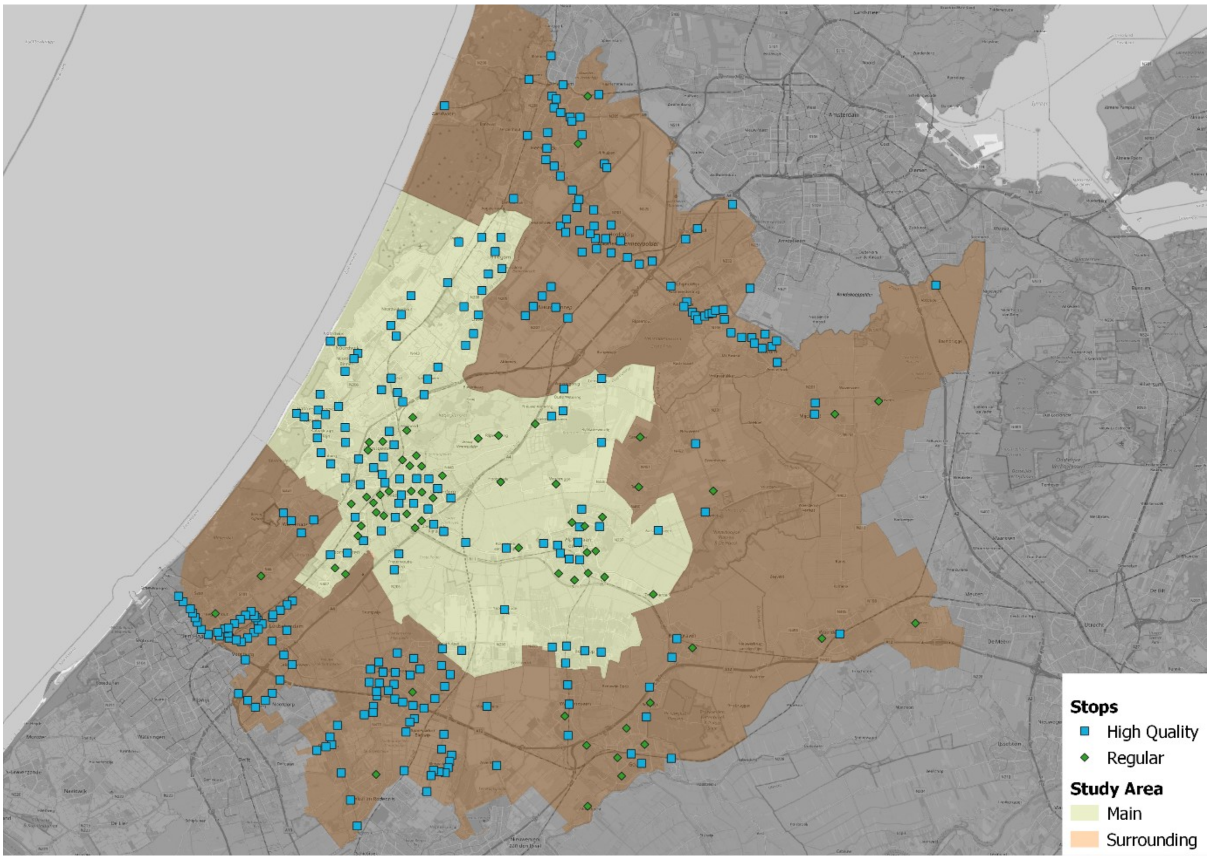

Figure 7.1: All high quality and regular stops without DRT and bicycle sharing (OpenStreetMap contributors, n.d.).

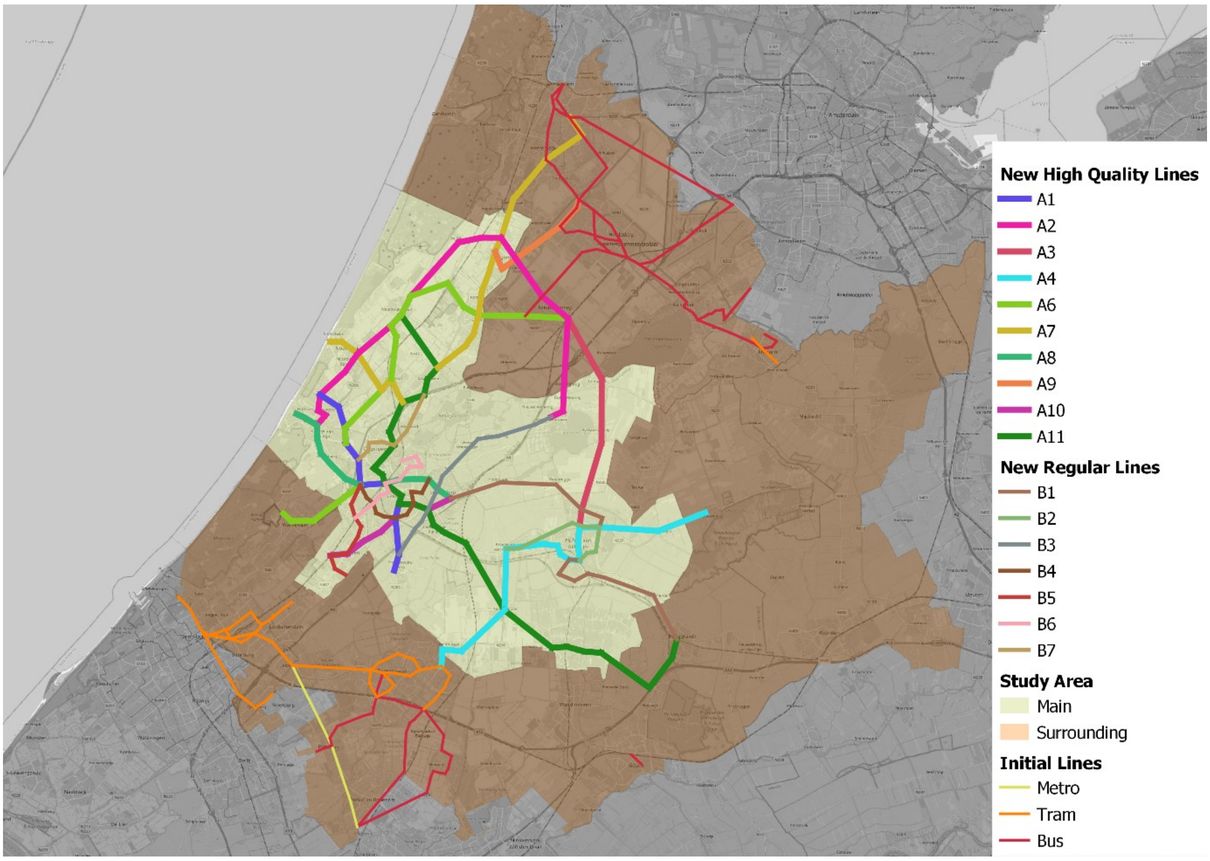

Figure 7.2: All high quality and regular lines without DRT and bicycle sharing (OpenStreetMap contributors, n.d.).

7.2. Including DRT

Using the same high quality stops and lines of the previous network design, a new network design was made that uses a DRT service instead of a regular fixed line. Figure 7.3 shows the resulting high quality and DRT stops. Also, different zones for the DRT services were created where individual services could operate. Another option is to operate the whole study area as one DRT service. As can be seen in Table 7.3 both options required a minimum of six vehicles. In this report, no choice was made because the effects on the criteria and the rest of the network was the same for both options. Either way, the number of TTH that were required, was 1462, as shown in Table 7.4, which was significantly lower than the maximum of 1601, leaving room for improving the high quality lines or expanding the DRT services.

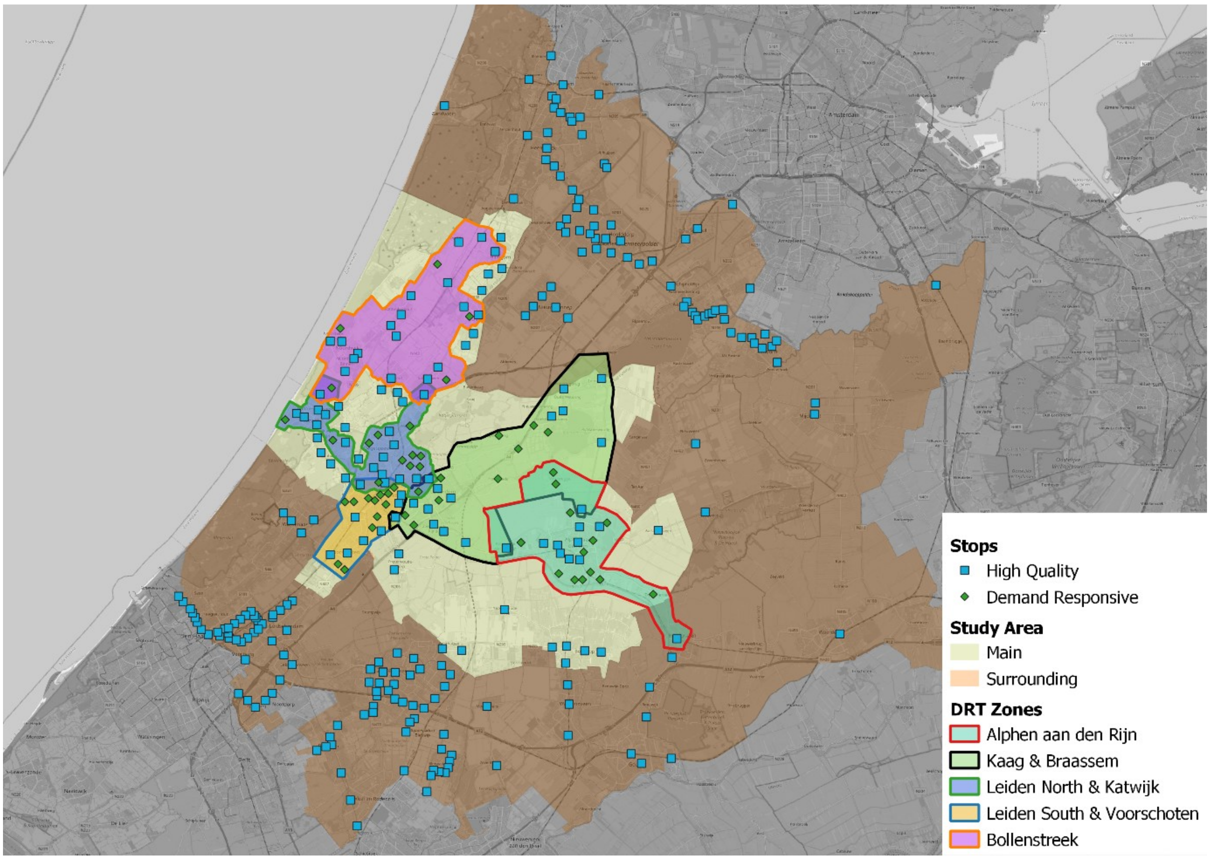

Figure 7.3: All high quality and DRT stops and DRT zones without bicycle sharing (OpenStreetMap contributors, n.d.).

Table 7.3: Number of stops per DRT zone and the minimum number of vehicles required per zone for the DRT network design without bicycle sharing.

DRT Zone	**Number of High Quality Stops**	**Number of Demand Responsive Stops**	**Total Number of Stops**	**Minimum number of vehicles in each zone**
Alphen aan den Rijn	11	13	24	1
Kaag & Braassem	16	12	28	1
Leiden North & Katwijk	18	13	31	2
Leiden South & Voorschoten	10	13	23	1
Bollenstreek	20	5	25	1
Total main study area	93	51	144	6

Table 7.4: Number of timetable hours used per service for the DRT network design without bicycle sharing.

	Timetable hours
High Quality	1350
DRT	112
Total	1462

7.3. Including Bicycle Sharing

In the third and fourth network designs, some stops were equipped with shared bicycles. This third network used regular lines instead of DRT services. Figure 7.4 shows all the stops with the corresponding required types of service, with the number of each stop type given in Table 7.5. A network consisting of 8 high quality lines and 6 regular fixed lines was drawn through these stops, as is shown in Figure 7.5. Again, several lines run almost in a loop as a result of combining multiple line segments. In total, 1602 timetable hours were used in this network, as can be seen in Table 7.6. Partly because of rounding the number of hours, this number resulted in being slightly above the maximum of 1601 TTH. Also, the uncertainties of the actual driving and stopping time of all routes might result in a larger difference than one hour, which could furthermore be eliminated during the detailing of the timetable.

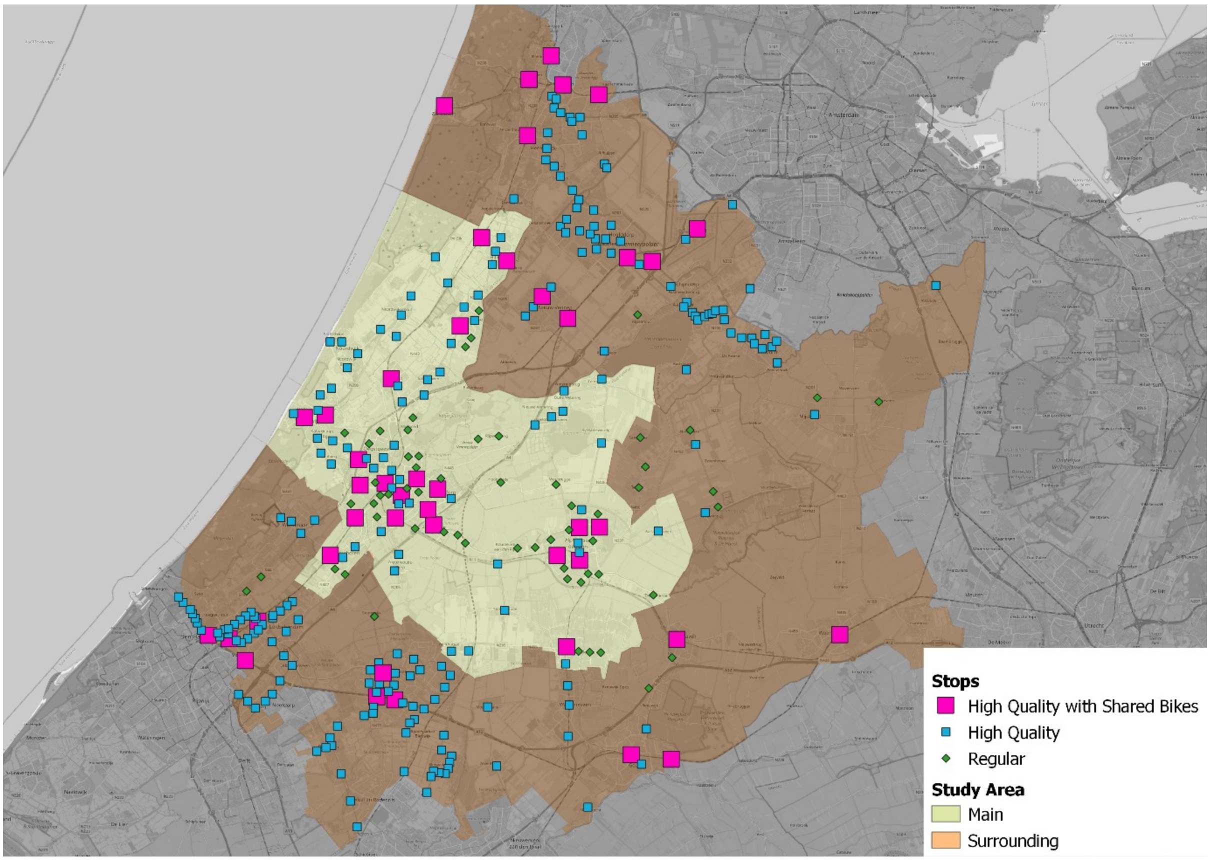

Figure 7.4: All high quality and regular stops of the network with shared bicycles but without DRT (OpenStreetMap contributors, n.d.).

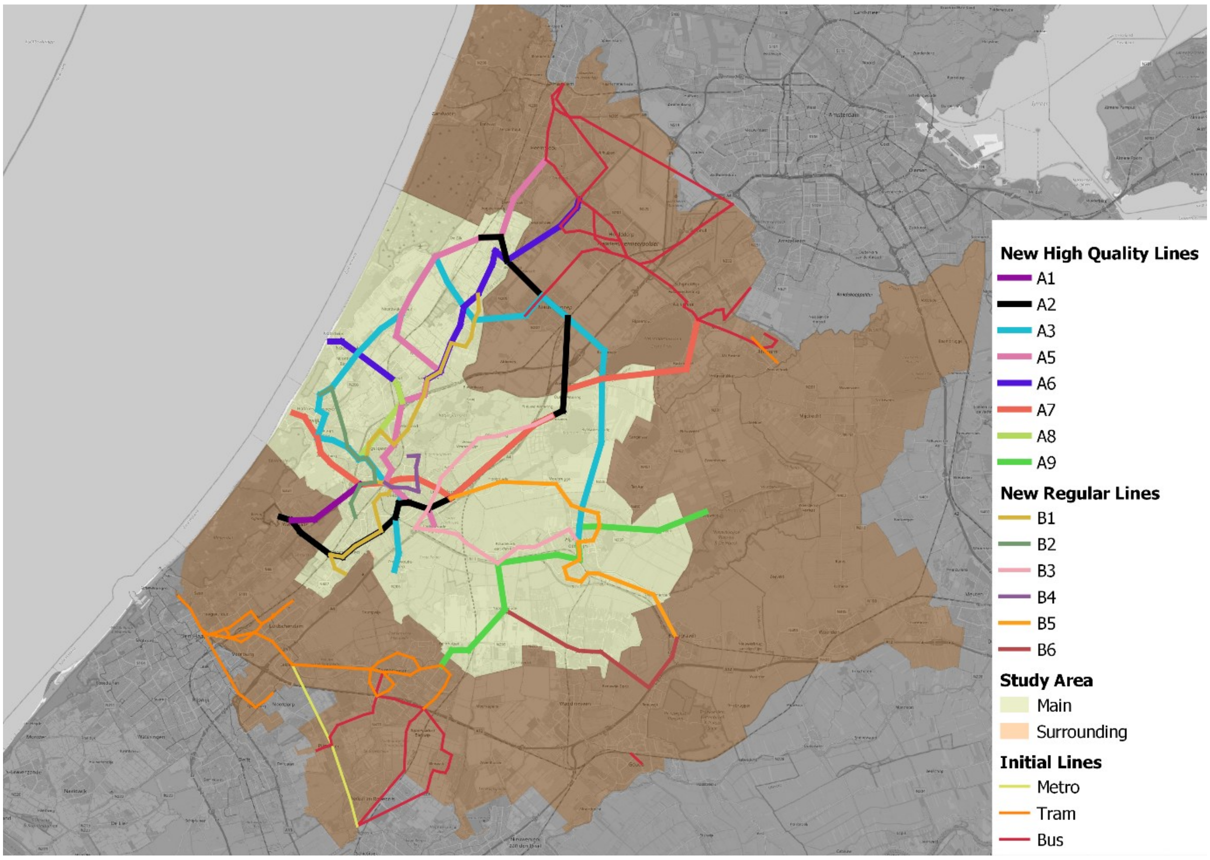

Figure 7.5: All high quality and regular lines of the network with shared bicycles but without DRT (OpenStreetMap contributors, n.d.).

Table 7.5: Number of stops required for each stop type in the main study area for the network with shared bicycles but without DRT.

Stop type	**Number of stops**
High Quality with Shared Bikes	22
High Quality	61
Regular	46

Table 7.6: TTH used to create the network with shared bicycles but without DRT.

	Timetable hours
High quality	1258
Regular	344
Total	1602

7.4. Both DRT and Bicycle Sharing

Finally, for the fourth bus network, the same high quality stops and service as for the previous network were used. Again, a set of DRT stops, which can be found with the accompanying high quality stops in Figure 7.6, was determined in order to comply with all criteria. Several zones for different DRT services were created. Similarly to the second network design, there is no difference in the required number of vehicle when using these zones versus using the complete main study area as a single DRT zone, as can be seen in Table 7.7. The number of TTH required for this network was much lower than the maximum of 1601, as can be seen in Table 7.8, leaving a lot of room for further improvements.

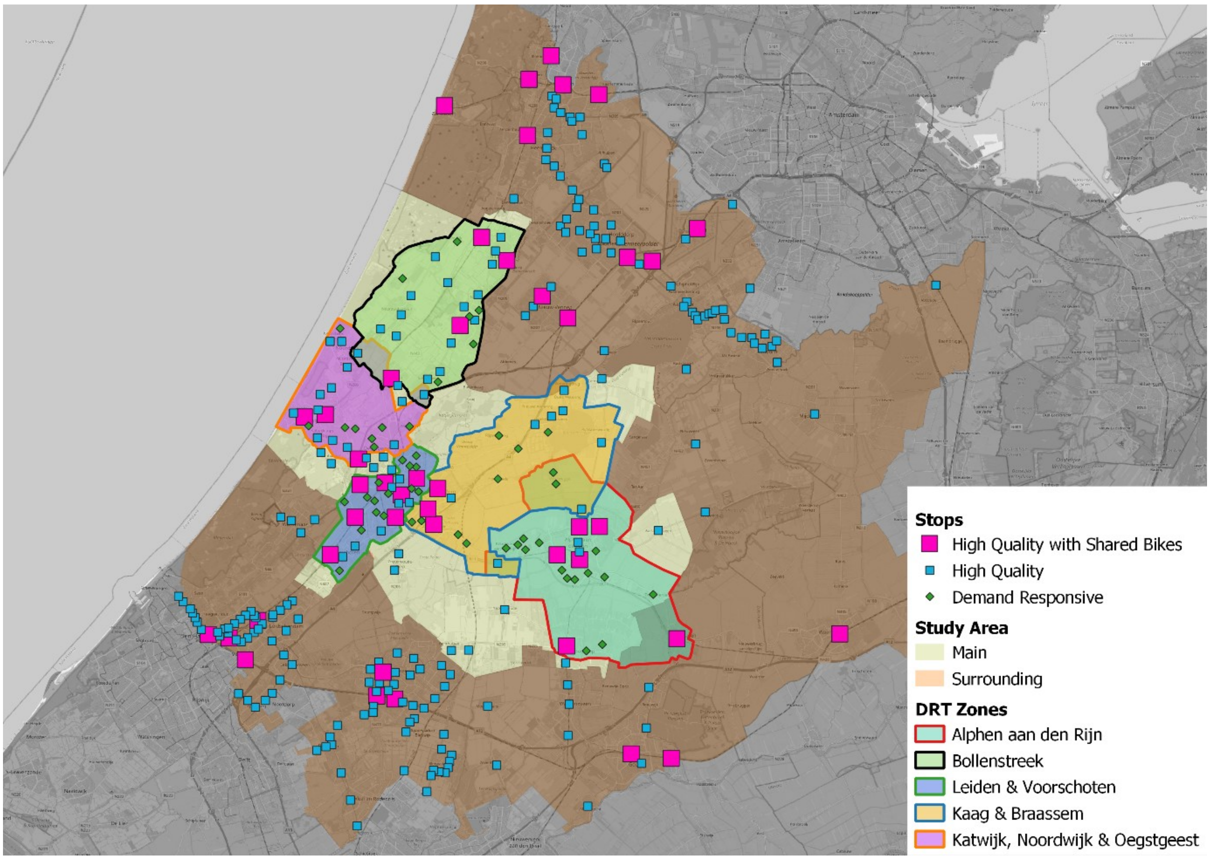

Figure 7.6: *All high quality and DRT stops and DRT zones with bicycle sharing (OpenStreetMap contributors, n.d.).*

Table 7.7: Number of stops per DRT zone and the minimum number of vehicles required per zone for the DRT network design with bicycle sharing.

DRT Zone	**Number of High Quality Stops**	**Number of Demand Responsive Stops**	**Total Number of Stops**	**Minimum number of vehicles in each zone**
Alphen aan den Rijn	10	16	26	1
Bollenstreek	21	6	27	1
Leiden & Voorschoten	14	15	29	2
Kaag & Braassem	11	10	21	1
Katwijk, Noordwijk & Oegstgeest	17	8	25	1
Total main study area	83	53	136	6

Table 7.8: TTH used to create the network with both shared bicycles and DRT

	Timetable hours
High Quality	1258
DRT	112
Total	1370

8. Evaluating & Comparing Designs

In this chapter, the four different network designs were evaluated using the methods discussed in Section 3.2.5. and compared based on the number of trips that were expected to be made by PT and the resulting passenger kilometres. In this evaluation the passenger kilometres were defined as the straight distance between the origin point and the destination point. In Section 8.1, the resulting performances were presented and compared. Then, Section 8.2 discussed the comparison with the existing bus network. Finally, Section 8.3 concluded with what these results meant for the bus network designs.

8.1. Performance Comparison

In order to improve the comparisons between the different network designs, two baseline networks were also evaluated, which consisted of only the train services and external bus, tram, and metro services as described in Section 6.2. Similar to Section 6.2, one of the baselines also included the effects of bicycle sharing while the other did not. In Table 8.1, the estimated number of trips and passenger kilometres is shown for both baselines and the four bus network designs. In these calculations the number of trips that relied on the DRT service, were not included, because it was expected that these service attract very few passengers. The goal of the DRT service was to provide the coverage function and give people the opportunity to travel if they are dependent on PT. This goal cannot be expressed in these numbers.

Table 8.1: Total number of trips and passenger kilometres of each network design.

Network	**Number of trips**	**Passenger kilometres**
Base without shared bikes	4.639	73.466
Base with shared bikes	6.758	102.425
Design 1: no shared bikes and no DRT	14.428	209.978
Design 2: no shared bikes but with DRT	13.852	200.898
Design 3: shared bikes but no DRT	17.584	244.425
Design 4: shared bikes and DRT	17.066	237.716

The inclusion of bicycle sharing caused a large increase in the number of trips and passenger kilometres. The switch from regular fixed lines to DRT services resulted in a seemingly small decrease of trips. In order to make a more pure comparison of only the new trips and passenger kilometres of each network design, the results of the baselines were subtracted from the results of the corresponding network designs. The results of designs 1 and 2 were reduced by the results of the baseline without shared bicycles and the results of designs 3 and 4 by the results of the baseline that included shared bicycles. Furthermore as mentioned in Chapter 7, for each design a different number TTH was used. Therefore, after the reduction by the baseline, the new results were divided by the number of TTH that was used for each bus network design, giving the number of trips per TTH and the passenger kilometres per TTH for each design, which are given in Table 8.2.

Table 8.2: Reduced results and results per TTH of the four different network designs.

	Reduced number of trips	**Reduced passenger kilometres**	**Timetable hours used**	**Trips per timetable hour**	**Kilometres per timetable hour**
Design 1	9789	136512	1589	6,16	85,91
Design 2	9213	127432	1462	6,30	87,16
Design 3	10826	142000	1602	6,76	88,64
Design 4	10308	135291	1370	7,52	98,75

From these results, it can be seen that the effects of shared bicycles were significant. Design 3, which included shared bicycles but no DRT service, showed an increase of approximately 10 percent in the number of trips per TTH and 3 percent in the passenger kilometres per TTH. The difference between these percentages showed that the average trip distance decreased, which might be explained by the attractiveness of the train because these services offer high speeds for longer distances. For shorter distances, the added egress range increases the number of destinations that were reachable, resulting in a larger share of relatively short trips. It should be noted, that the number of trips shorter than the average cycling distance were not included in these results, as can be read in Section 3.2.4. Therefore, there was only limited competition of these "short" trips with the use of the bicycle for the complete trip. Furthermore, because the effects of shared bicycles at train stations were not included in this comparison as these were already removed by the baseline results, the total effects of offering shared bicycles on the complete PT system can be expected to be even greater.

The standalone effects of DRT services were much smaller. Comparing design 2, which included DRT services but no shared bicycles, to design 1, which used neither, showed an increase of only 2 percent in the number of trips per TTH and 1 percent in the passenger kilometres per TTH. By including shared bicycles as well, as was done in design 4, the effects were much larger: an increase of 11 percent in both trips and passenger kilometres per TTH was achieved compared to design 3, which included only shared bicycles. However, the costs of the DRT service were very uncertain. A range was created in order to find how much these costs were allowed to increase before the effects of the DRT service became negative. Figure 8.1 shows this range with the DRT cost factor equal to 1 being the assumed costs and the DRT cost factor of 2 being twice the amount of costs. For design 2, which did not include bicycle sharing, the costs were only allowed to be only 1,3 times as high a assumed before fixed lines were more efficient. By including bicycle sharing as well, as was done in design 4, this factor increased to 2,4. Furthermore, using the earlier assumed costs of DRT (i.e. the DRT cost factor of 1) an increase of 22 percent in the number of trips per TTH and 15 percent in passenger kilometres per TTH was achieved by including both DRT and bicycle sharing services.

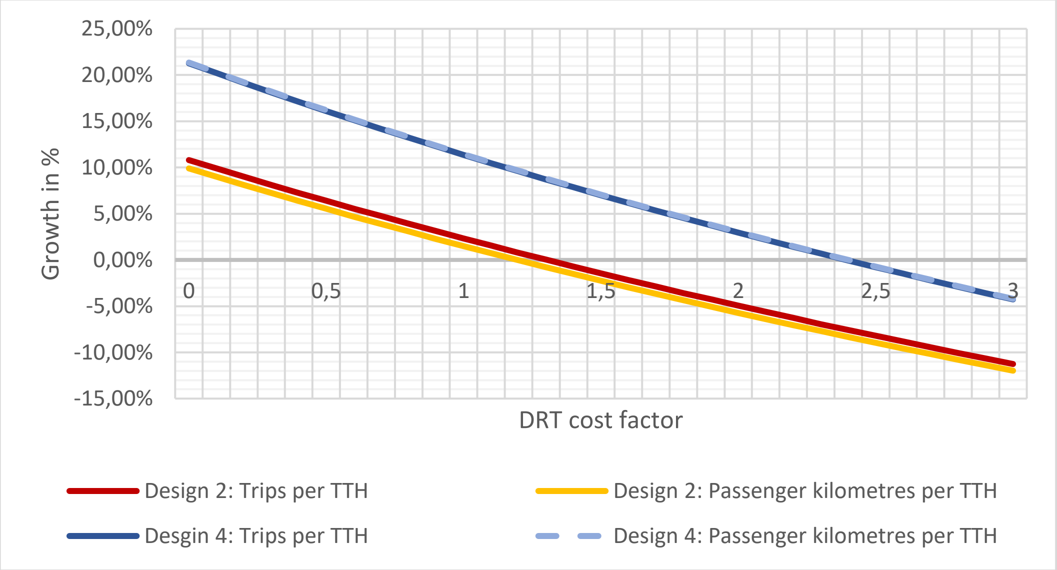

Figure 8.1: Range of the growth of the effects of DRT when considering different DRT cost values.

8.2. Comparison to the Existing Network

In the previous section a comparison was made between the four bus network designs. A further comparison of these designs with the existing bus network proved to be much more difficult, as discussed in Section 8.2.1. Therefore, no such comparison was made. However, instead of a quantitative comparison, several differences were observed between the network designs and the existing bus network, which are discussed in Section 8.2.2.

8.2.1. Limitations

Several limitations in the calculations prohibited a comparison with the existing network. First of all, the results from these calculations were the number of trips, while the available data from the existing network contained the number of boardings and alightings. Because travellers can board multiple times in the case of transfers, the number of the existing network were inflated compared to the calculations. At the same time, the calculations included trips made by external services (i.e. train services) as well. Furthermore, trips to or from outside of the surrounding area were not considered. In the NRM data, these trips made up of 20 percent of all trips to and from the main study area, which included trips with a longer distance that attract relatively many PT users as a result of the high speeds of the train services. With the buses connecting to many train services, this reduced a significant number of passengers using the public transport system. Shorter trips that were considered cyclable, were also not included in the total number of PT trips that resulted from the calculations. Although these trips were considered cyclable, there still exists a group that chooses PT over cycling for these distances, reducing the total number of trips in the calculations even further. One of the largest effects that reduced the results from the calculation, were the assumed maximum access and egress distances. By assuming travellers would not access or egress farther distances, the calculation time was kept to a workable amount. However, as these numbers were already assumed to be conservative, a large number of travellers was expected to be willing to cover greater distances, but these were again not included in the results. Finally, these networks were neither finalized nor optimized, meaning that some routes still had to be adjusted and frequencies had to be set throughout the day in order to fit the demand better. During the rush hours when a large proportion of trips take place, the frequencies were likely higher than currently assumed, which would have increased the share of people taking PT as well. These limitations were the same for all designed networks, meaning that it was possible to compare them to each other, but not to the existing network. For a better quantitative comparison, either a more complicated estimation had to be made or the same calculations had to be performed for the existing network. Due to time constraints neither of these options were possible for this report.

8.2.2. Observations

By comparing the network designs themselves to the existing bus network, several key differences were found. One of the first things that were noticed, was bus line 400 between Leiden and Zoetermeer which was shortened significantly in the new designs even though it was the most popular bus service of the whole concession. Multiple reasons for this were found, which are further discussed in Section 9.2.1. The other differences that were found, showed more opportunities for policy makers and network designers. First, was the use of the train station in Nieuw-Vennep as an important transfer hub. In the existing bus network, this station was served by only two lines, both with a frequency of just once per hour: one line connecting to Lisse and one line connecting to Hillegom and further via other villages to Leiden. Three other lines, including one R-Net line, passed Nieuw-Vennep in order to offer a direct connection to Schiphol Airport via the A4 motorway which runs parallel to the train service between Nieuw-Vennep and Schiphol. In each of the new networks, high quality services from the same villages were created that came together at the train station in Nieuw-Vennep, where a connection with the train towards Schiphol was offered. New connections between both sides of the A4 were offered because in the existing network no opportunities existed to travel between Roelofarendsveen, Leimuiden, and Alphen aan den Rijn on the one end, and Nieuw-Vennep, Hillegom, and Lisse on the other without requiring a large detour to make a transfer in either Leiden or Schiphol.

For passenger travelling to Schiphol, the additional transfer in Nieuw-Vennep was a disadvantage. The total travel times for these passengers probably did not increase significant if at all because of the train service between Nieuw-Vennep and Schiphol, but the extra transfer decreases the attractiveness of the service, especially considering that travellers to the airport are more likely to carry a lot of luggage. A large number of TTH was won by not driving all the way to Schiphol, which resulted in more TTH to be used for other services or for increasing the frequencies. Similarly, a large transfer hub with many R-Net lines serving several key destinations in both Haarlem and Hoofddorp already existed in Hoofddorp near the Spaarne Gasthuis hospital. Again, there was an opportunity for mostly Hillegom to benefit from the existing services by introducing a connection to this bus station. Furthermore, this line allowed for a new, previously non-existing connection between Hillegom and this large regional hospital. In both cases hubs were used that followed the advice from McLeod et al. (2017) of “embracing and managing transfers”, fitting with the patronage practice of introducing mobility hubs.

The use of the other patronage practice of straightening lines was especially strong in the town of Noordwijkerhout. In the existing network, two lines snake through the town with a frequency of once or twice per hour. A great opportunity for straightening these lines exists in Noordwijkerhout as a large provincial road goes right through the town. In all new network designs, all routes serving Noordwijkerhout made use of this road. When assuming the given criteria for the high quality services, only four stops were enough to serve the complete town, even without requiring shared bicycles or a DRT service. The new routes more than halved the driving time from one end of the Noordwijkerhout to the other end. For the travellers, the greater access and egress distances were biggest disadvantage. Although these distances were within even the walking criteria for most travellers, for some these could become too far. Many more examples of straightening and consolidating lines existed in the network designs, but the case for Noordwijkerhout was the most consistent in all the designs.

8.3. Conclusions

Shared bicycles affect the maximum acceptable egress distances of PT stops, which allowed for less stops and stops along faster roads, resulting in overall shorter driving times of the bus services. In turn, the shorter driving times allowed for more TTH to be spend on introducing different high quality route segments. The combinations of the effects of the introduction of shared bicycles during the designing of the bus network resulted in an increase of at least 10 percent in the number of trips per TTH and 3 percent in the passenger kilometres per TTH. On the other hand, the effects of introducing DRT during the designing of the bus networks were very dependent on the costs as was shown in Figure 8.1. Unless the costs were much lower than assumed, the effects of including only DRT showed increases of only a couple percent. When bicycle sharing was included as well in the network design, the effects of DRT were positive up to almost 2,5 times the assumed cost. For higher costs, it was more efficient to operate fixed line services. Especially the combination of both practices offered a much more efficient coverage functionality allowing for a more effective patronage network.

Furthermore by “embracing” the use of transfers, the resources were much more efficiently used, which allowed for the opportunity of introducing more high quality services. By accommodating the access by bicycle, the access distances were increased which resulted in stops being located along faster roads and less stops being required. This further decreased the driving times of many routes, increasing the efficiency of the network.

9. Conclusion & Discussion

This report focused on the effects of combining both patronage and coverage practices in the design process of a bus network. The conclusions of this research are presented and discussed in Section 9.1. Then, the discussion, including the recommendations that resulted from this study, is presented in Section 9.2.

9.1. Conclusion

A societal challenge existed in order to draw more people to public transport, specifically the people that would otherwise use their car. This challenge was especially big for bus services between locations that were not served by the train network. Designing the network primarily for the goal of increasing the patronage comes at the cost of the existing coverage functionality of the PT network. Literature describes many examples of how these patronage goals can be achieved in practice, but the coverage function is often neglected in this literature. Most research on the coverage function focussed either on non-existing cases, very small areas, or on introducing additional services to an existing network. What the effects are on a large scale when the coverage function is included at the start of the design, was unclear. For this reason, the following research question was developed:

What are the effects of including coverage practices in designing a patronage based bus network for a real world case in the Netherlands?

This question was answered by following a design process for a bus network. Each step of this process was taken by answering a sub-question. By first looking at how these sub-questions were answered, which was done in Section 9.1.1, the main research question was answered in Section 9.1.2.

9.1.1. Answering Sub-questions

1. **What is the design philosophy of the bus service?**

The design philosophy was the result of three smaller analyses: what were the emerging practices that had to be included, what segmentations existed between different trips, travellers, and locations, and what hierarchy fitted best for the new bus network designs. The emerging practices consisted of patronage practices and coverage practices. The patronage practices straightened bus lines in order to offer a faster more frequent service and introduced mobility hubs were transfers were accommodated. The coverage practices had a large focus on bicycles, both for accessing the bus network by providing parking facilities for bicycles and for egressing by offering shared bicycles at key locations. Another emerging coverage practice was the use of DRT services, which offered a PT option for the people that were not able to use a bicycle or for locations that were too far from any stop.

The segmentations showed that the frequencies and distances of different trips varied for different trip purposes. For each traveller age group and level of urbanization, these frequencies and distances varied as well. In order to ensure the coverage function, it helped to pay extra attention to the people groups that were less likely to be able to use a bicycle (i.e. the oldest age group). This attention did not only go to the locations of where these people live but also to the locations were they wanted to go to. For the DRT service, these locations were of extra importance, because these people were one of the target groups of this service.

In the hierarchy, the focus was on the high quality services, including train services, which had to goal to provide most of the patronage function of the PT network. The hierarchical level below this service consisted of regular fixed line services connecting to the high quality services in order to expand the coverage of the high quality services. The DRT service connected a large number of stops to the high quality service, but without a fixed line. In Figure 9.1, these services are given, showing a schematic view of the design philosophy.

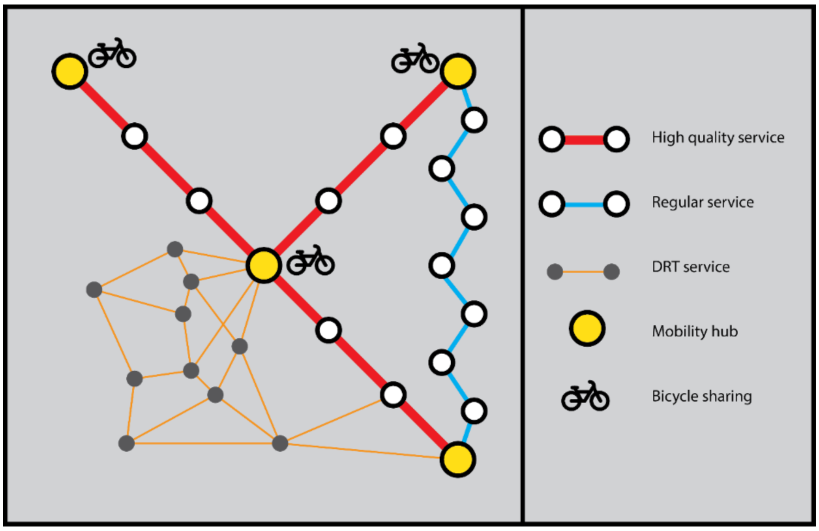

Figure 9.1: Schematic network example of the proposed services.

2. What are the objective and criteria of the bus network?

The focus of the bus network designs were on increasing the ridership and reducing the number of car trips, which fitted best with the patronage goals. For that reason, the objective was also chosen from a patronage perspective. The objective of the bus network designs was to attract as many trips as possible. The coverage function was guaranteed by the criteria. Within the constraint of the maximum number of timetable hours, it was stated that, based on the existing criteria, at least 80 percent of all inhabitants and destinations had to be served within an acceptable access and egress distance of a high quality service. Also, 95 percent had to be served within an acceptable access and egress distance of any service. The acceptable distances are given in Table 9.1 for the high quality service and in Table 9.2 for the regular services. These distances are larger than currently used in the network requirements, but were considered conservative from the possibilities shown in other research. For the demand responsive service the acceptable distances were set to 400 metres. In terms of frequency the high quality service required an average frequency of at least four times per hour while the regular service had to have an average frequency of twice per hour. The DRT service required one vehicle with driver to be available for approximately 25 stops served by this service.

Table 9.1: Overview of criteria per level of urbanization for a high quality service.

		Distances in metres				
Level of urbanization	**Minimum frequency**	**Access**	**Egress by bike**	**Egress by walking**	**Egress to hospitals**	**Egress to shopping areas**
Highly urbanized	4	1100	1100	700	500	500
Urbanized	4	1200	1200	750	500	500
Moderately urbanized	4	1300	1300	800	500	500
Little urbanized	4	1400	1400	850	500	500
Not urbanized	4	1500	1500	900	500	500

Table 9.2: Overview of criteria per level of urbanization for a regular service.

		Distance in metres			
Level of urbanization	**Minimum frequency**	**Access**	**Egress**	**Egress to hospitals**	**Egress to shopping areas**
Highly urbanized	2	450	450	200	450
Urbanized	2	500	500	200	450
Moderately urbanized	2	550	550	200	450
Little urbanized	2	600	600	200	450
Not urbanized	2	650	650	200	450

3. What are the characteristics of the study area?

The characteristics of the study area were split in two types: demand and supply. The demand consisted of origins and destinations. Using the model described in Section 3.2.3, many different data points were combined in order to find the locations of where demand for mobility existed. By removing the demand that was already served by the train services and the surrounding bus, tram, and metro services, the demand was found that remained unserved, which is shown in Figure 9.2. In total 1601 TTH were available to design the network that served this remaining demand.

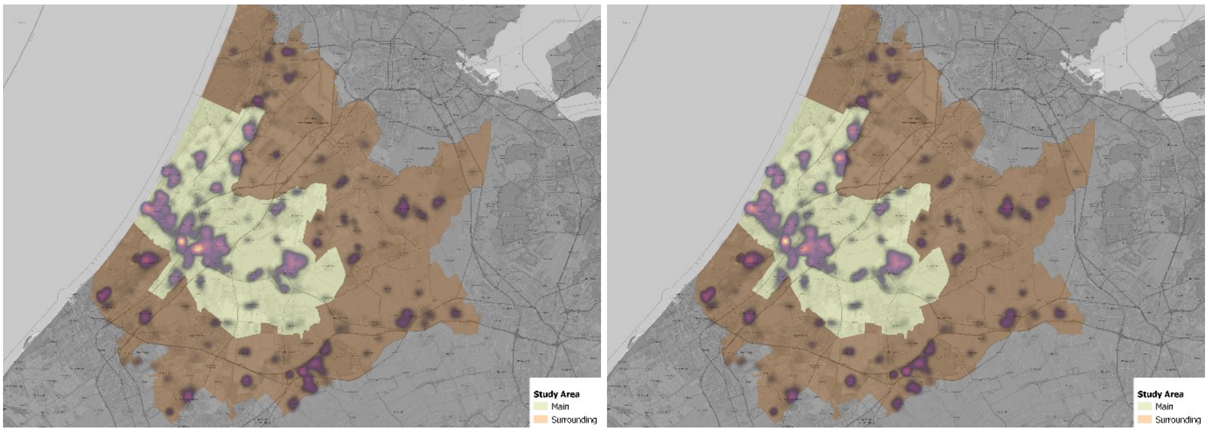

Figure 9.2: Demand remaining for the designs to serve (left: without shared bicycles, right: including bicycle sharing) (OpenStreetMap contributors, n.d.).

4. What are possible bus network designs?

In order to find the effects of both the bicycle sharing and the DRT service, four different bus networks were designed: one network using neither practice, one network incorporating only bicycle sharing, one with only DRT, and the fourth combining both practices. The creation of these bus network designs was done in two steps: first, the stop locations were determined by applying the stop location model which was described in Section 3.2.4, then, the lines were drawn between these stops using the approach that was also presented in Section 3.2.4. These methods built upon the earlier determined criteria and the demand and supply found for the previous sub-question. The use of DRT services over fixed line services did not affect the lines of the high quality service, but the use of shared bicycles did. Therefore, one set of high quality lines was used in both designs without shared bicycles and another set was used for both design with shared bicycles. The high quality and regular lines for the design without DRT and shared bicycles are shown in Figure 9.3. The DRT stops and zones for the same high quality network design without shared bicycles are shown in Figure 9.4. The bus network designs that did include shared bicycles are shown in a similar fashion in Figures 9.5 and 9.6.

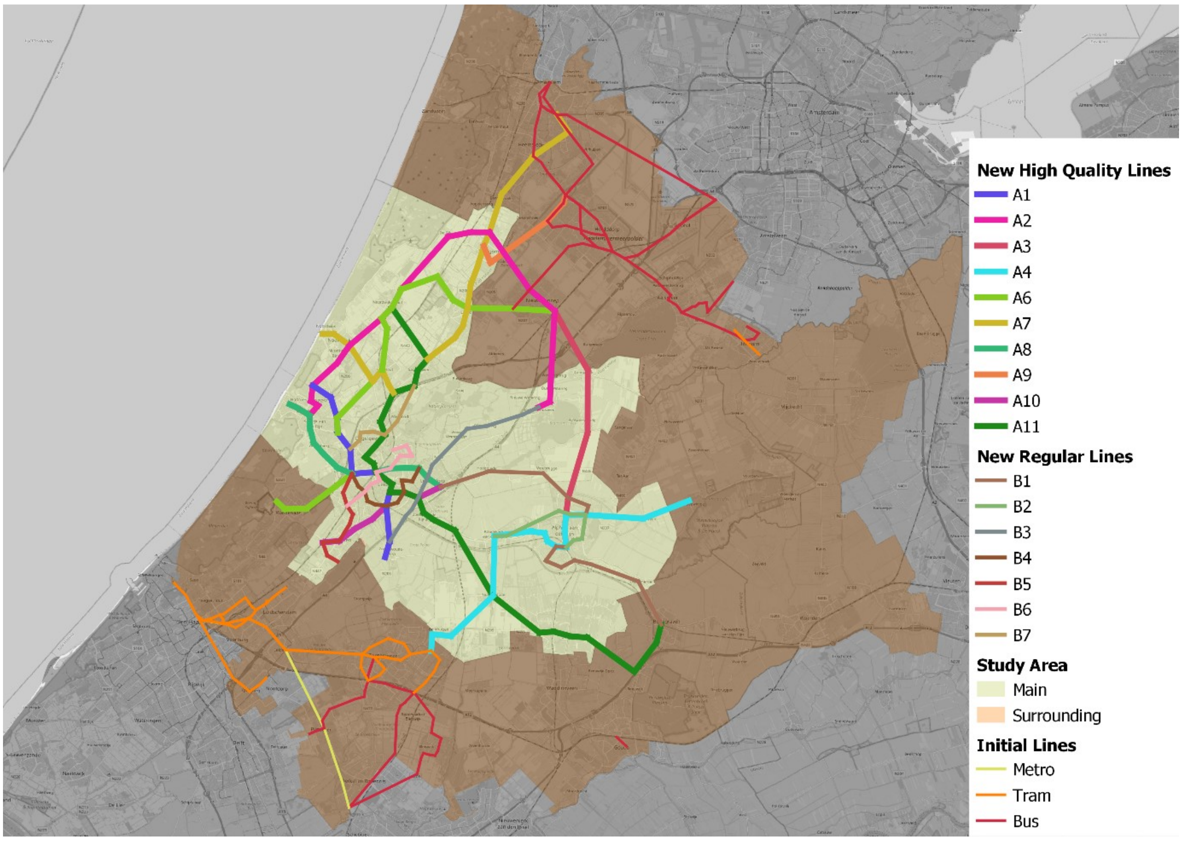

Figure 9.3: The high quality and regular lines of the design that used regular fixed lines and no shared bicycles (OpenStreetMap contributors, n.d.).

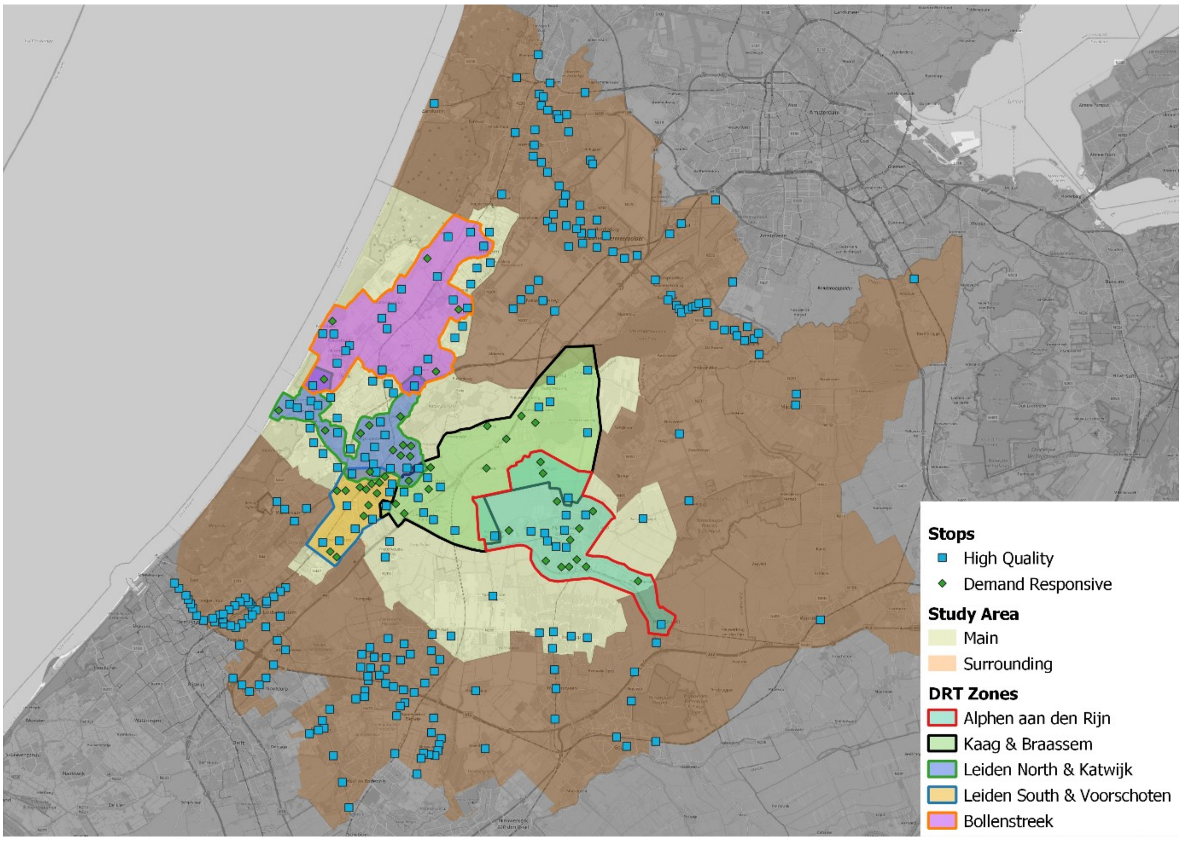

Figure 9.4: The stops and zones for DRT service supporting the high quality network that did not incorporate shared bicycles (OpenStreetMap contributors, n.d.).

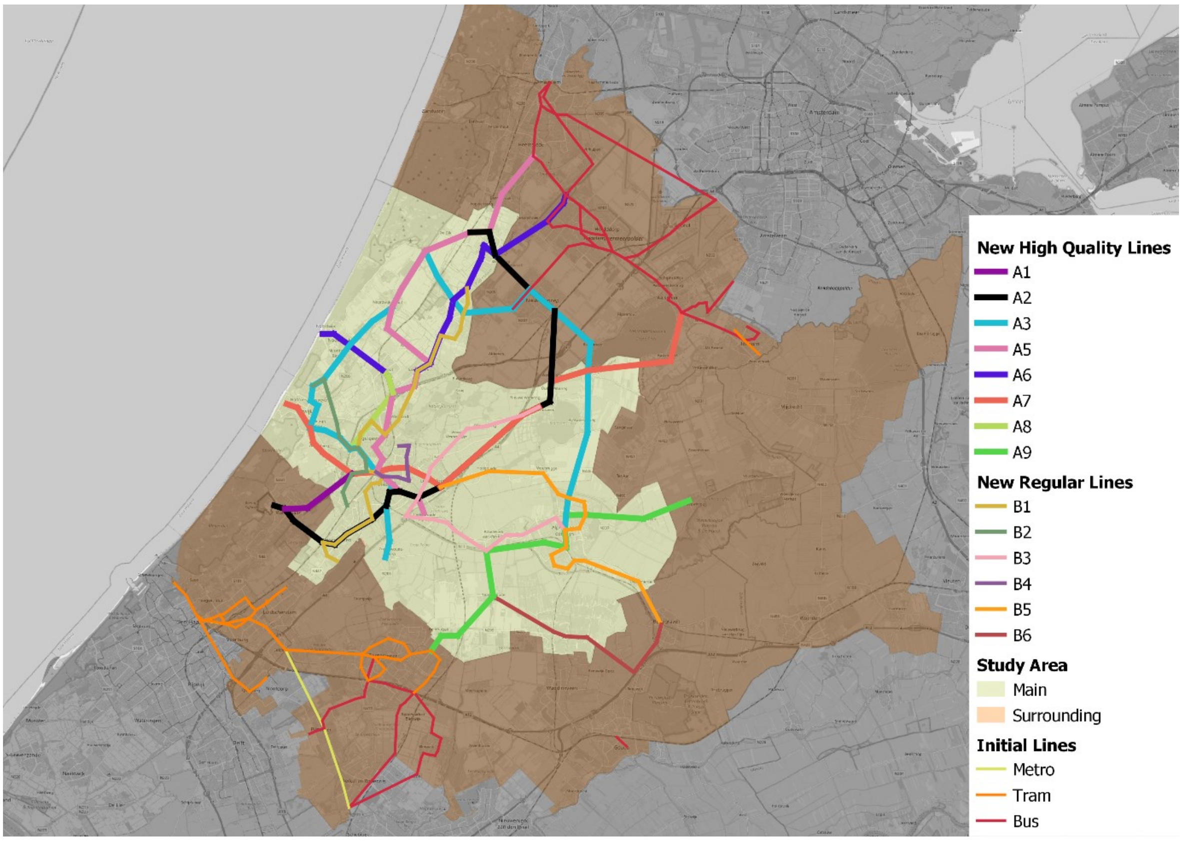

Figure 9.5: The high quality and regular lines of the design that used regular fixed lines and shared bicycles (OpenStreetMap contributors, n.d.).

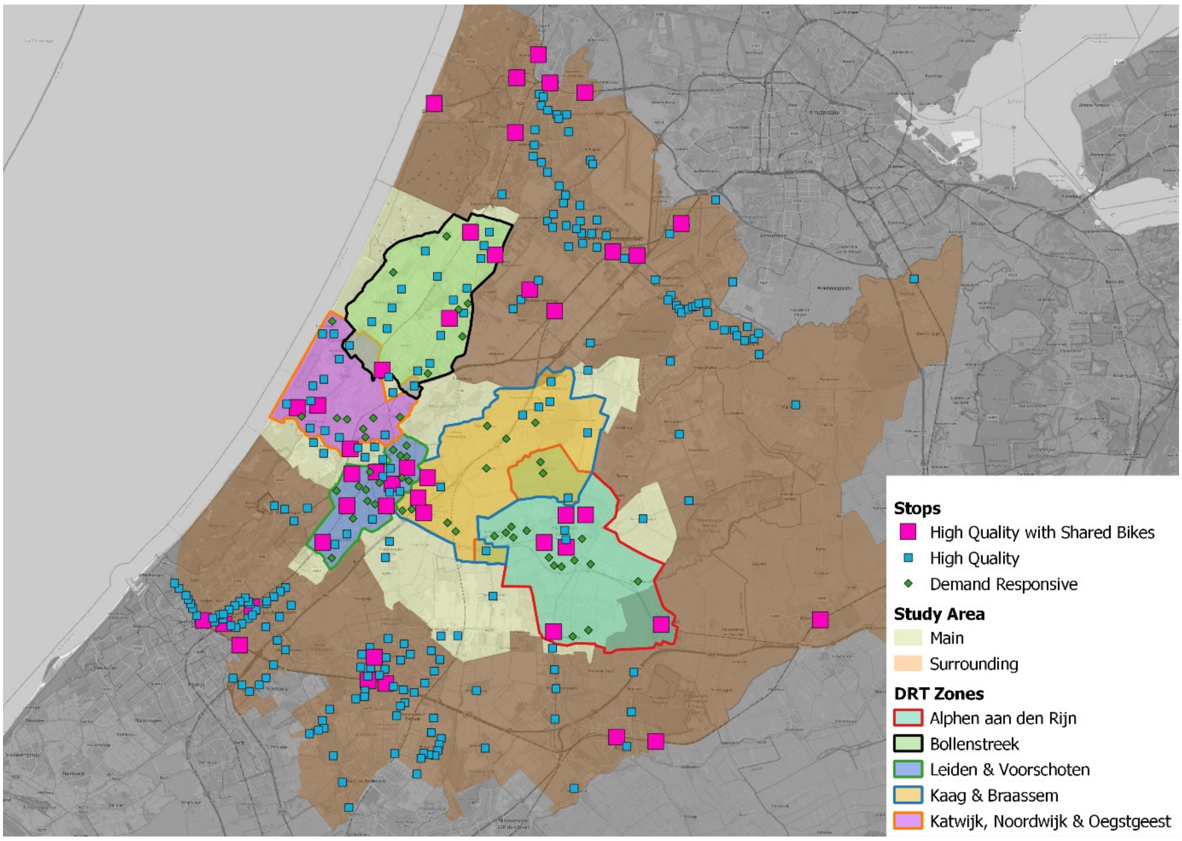

Figure 9.6: The stops and zones for DRT service supporting the high quality network that did incorporate shared bicycles (OpenStreetMap contributors, n.d.).

5. **How do the different designs perform and differ from each other?**

The different designs were analysed on their performance by looking at the estimated number of PT trips that were attributed to the new network designs, as well as at the estimated passenger kilometres. Because the networks used varying numbers of TTH, the number of trips per TTH and the passenger kilometres per TTH were calculated in order to improve the comparison, resulting in the numbers given in Table 9.3.

Table 9.3: Trips and passenger kilometres per timetable hour for each network design.

Network	**Trips per TTH**	**Passenger kilometres per TTH**
Design 1: no shared bikes and no DRT	6,16	85,91
Design 2: no shared bikes but with DRT	6,30	87,16
Design 3: shared bikes but no DRT	6,76	88,64
Design 4: shared bikes and DRT	7,52	98,75

By including shared bicycles in the design process, the egress distances could be increased resulting in a faster network, which attracted approximately 10 percent more trips per TTH and 3 percent more passenger kilometres per TTH. The effects of replacing the fixed lines by DRT services were only marginal, unless the actual costs turn out to be much lower than assumed in this report. When the DRT services were introduced alongside the shared bicycles, a much larger increase of the trips per TTH and passenger kilometres per TTH was found. In this case, the costs of the DRT service were allowed to be almost 2,5 times as high as assumed before fixed lines become more efficient. The combination of introducing both shared bicycles and DRT services allow for an efficient method of maintaining the coverage functionality while increasing the effectiveness of the patronage network. The use of the bicycle as an access mode further enhanced the efficiency of providing the coverage function and thus allowed to improve the patronage as well. The effectiveness of the patronage network was also increased by making use of strategic transfer locations instead of operating multiple parallel services.

9.1.2. Answering Main Research Question

By looking at the answers of the sub-questions and the underlying methods used to answer these questions, an answer was formulated for the main research question, which was stated as follows:

What are the effects of including coverage practices in designing a patronage based bus network for a real world case in the Netherlands?

The inclusion of coverage practices in the design of a patronage based bus network affected multiple steps of the design process and the individual outcome of these steps. A patronage based network relies on a high quality bus service, with high speeds and frequencies. If this high quality bus service also has to provide a coverage function the high speeds and frequencies are lost. Therefore, additional services have to be provided in order to ensure the coverage function. Offering parking facilities in order to provide the bicycle as an access mode was already common place for many bus stops, but the effects of the bicycle as an access mode were often not taken into account in the network design. Similarly, shared bicycles as an egress mode can be used as well to increase the reach of bus stops. Additional services alongside the high quality service also have to be provided in the form of DRT or regular fixed lines in order to serve the people that are unable to use the bike or for whom the distance to the stop is too far even when using the bike. As a result, a two layered bus service is required in the overall PT hierarchy. By including bicycles as access mode, the maximum access distances are allowed to be larger than is currently required for R-Net bus services. As a result, stops can be located along faster roads and less detours are required without losing on the coverage functionality, allowing for shorter driving times. By reducing the driving time, many timetable hours were saved, which were in turn used to provide new connections and higher frequencies. These effects enhanced the attractiveness of the PT system for many passengers, increasing the patronage. By providing an additional layer in the hierarchy, the high quality service is not required to serve hundred percent of all origins and destinations. A lower percentage also suffices as long as the second layer (i.e. regular fixed lines or a DRT service) serves the remaining origins and destinations.

The four different bus network designs show that a large network of high quality bus services, supplemented by the existing train services, is possible without requiring additional timetable hours. The supporting fixed line or DRT services are used more tactically for the locations where the high quality services do not reach. Offering shared bicycles at certain stops allow the egress distances at these stops to also be increased beyond the existing R-Net criteria, which produced in an even faster high quality network providing more opportunities for high quality connections. As a result of the introduction of only shared bicycles in the network design, 10 percent more trips were made per timetable hour and 3 percent more kilometres per timetable hour were covered by the passengers. The effects of replacing the fixed regular lines by DRT services were more complicated to determine because of the uncertainty of the costs of the DRT services. Without the introduction of shared bicycles, the improvements in terms of trips per timetable hour and passenger kilometre per hour were only marginal, unless actual costs turn out to be much lower than assumed in this report. If the costs turn out to be higher, DRT services are less efficient than regular fixed lines. This changes when shared bicycles are introduced as well, additional growth in both number of trips per timetable hour and passenger kilometres per timetable hour was achieved unless the costs turn out to be up to 2,5 times as high as assumed in this report. Above this number, regular fixed lines would still be more efficient.

All in all, this report shows that a large network of fast and frequent bus services is possible for a large case area if the access by bicycle is accommodated and incorporated from the beginning of the network design. The effectiveness of the network in attracting passengers can be increased by providing shared bicycles at key locations possibly supplemented by DRT services as a replacement of regular fixed line services. The effects of the incorporation of the bicycle as access (and egress) lie mostly in the access (and egress) distance criteria that can be increased allowing for these high quality networks. DRT affects the network design mostly by saving on the costs of the regular fixed lines. Because further improvements can be made to the networks, these cost savings are greater than the loss of passengers by replacing the fixed lines by DRT services, especially when DRT is combined with bicycle sharing.

9.2. Discussion

This reports adds to the scientific knowledge by expanding on how services as demand responsive transport and bicycles sharing schemes affect a bus network design and also confirming the possibilities and opportunities of incorporating these practices. Especially the focus on the combination of these practices with a high quality bus network rather than train services adds new knowledge. Aside from this new knowledge, this research has also resulted in a newly developed model and approach to designing bus networks. The validation of these models are further discussed in Section 9.2.1. The development of this new design model means that the findings of this research can be compared with other locations. This report also had some limitations, as discussed in Section 9.2.2, that affect how the results and conclusions can be used in future research. In Section 9.2.3, several recommendations are given for this. Recommendations on how to use these findings on a societal level are given in Section 9.2.4.

9.2.1. Validation of the Models

The models and approaches that were used to develop the four network designs, are newly developed for this research. For the results it is important to be transparent of the limitations of these models. This section discusses the limitations that were specific for the design models, and what their effect was on the bus network designs, other assumptions and limitations are discussed in Section 9.2.2. First, the limitations of the stop location model are discussed, followed by the limitations during the creation of the lines. Finally, it is stated whether these models and approaches gave valid results despite their limitations.

Stop Locations

One thing that was noticed during determining the stop locations, was that the cluster centres resulting from the clustering algorithm gave very little insight. The centres were good locations in terms of the surrounding weight, but the effect of moving the point towards a road was unknown. This affected how optimal the stop locations were for both the weight that was served by the stop and the road that the stop was placed on, which in turn affected how many people used the stop and the average speed of the bus route. By determining the weight served per stop, this has partially been solved. Stops serving little weight were moved to roads where they served more weight. However, this extra step was time-consuming and required more steps and iterations to be taken. For all networks this problem existed, so they were designed similarly which allowed for comparison between the designs, even though the overall optimality of the networks was affected.

Another limitation was that the K-Means algorithm, was only performed on some sections of the study area at a time, resulting in duplicates of cluster centres that were close to each other. Also, because of the nature of the K-Means algorithm, some of the cluster centres served very little weight because they were in the middle of multiple areas with weight but too far from any of these areas to actually serve them. Usually for a K-Means algorithm, this would require more clusters in the section where it is performed. However, because the sections switched, some of these cluster centres remained. For this reason, the weight served per cluster centre was calculated in order to filter these out. In case of duplicates, only one stop was placed near them during the iteration in order to solve that problem. If demand existed for multiple stops, this would have showed up in subsequent iterations.

Creating Lines

As mentioned in Section 8.2.2, in all designed bus networks the absence of the most successful existing line, line 400 between Leiden and Zoetermeer, stands out. There are multiple reasons as to why. First is that the zones that were used, differed greatly in size and number of origins and destinations. For example, all of Hoofddorp was one zone, while Zoetermeer was divided over seventeen different zones. Differences like this made Hoofddorp and other larger zones stand out much more when looking at the origin-destination combinations with the most unserved trips. Combining all of the zones in Zoetermeer resulted in multiple origin-destination combinations that included Zoetermeer appearing at the top of the list with the most unserved trips.

Another reason is that there is a single value for the VF stating whether an OD combination was served or not. When many OD combinations had a VF that was close to this single value it appeared that many were served, while in reality many more passengers could have been attracted when a lower VF was offered. With the large number of train services between Leiden and Den Haag and an even greater number between Zoetermeer and Den Haag, it was possible that many OD combinations could have already have been served, albeit with a large VF. A direct service with a low enough VF could in this case still have attracted many extra passengers.

Also, the number of trips that were used for determining the lines, was only an estimation that was not yet corrected with actual revealed travel data, meaning that the number of trips used for this model could have been less than what is actually happening, but that is unknown. However, this difference is not of a magnitude that the demand for a successful bus line completely disappears.

Valid Results?
Due to the restrictions in the data, the resulting networks were not completely optimized. However, as stated in Section 2.1, it is very difficult to come with an optimized network. Although sub-optimal, the methods that were used did provide steps to maximize the results. Also, the limitations were the same for all the networks, which allowed for comparisons to be made between the four bus network designs. Furthermore, the network designs show the effects of the different design principles on both the lay-out of the network as on the performance of the network. Further improvements and detailing of the network would likely adhere to these principles, keeping at least similar effects.

9.2.2. Assumptions and Limitations

During this research, many assumptions that affected the outcome of the results, were used in the process of developing and analysing the different bus networks. In this section the main assumptions per chapter are discussed. First, the design context was developed with the goals of Zuid-Holland in mind to attract more passengers. A different transport authority might value the trade-off between patronage and coverage differently. With different goals in mind, the design context and thus the rest of the design process will change.

In the criteria, many assumptions were made, with the most important being the required percentage of origins and destinations that had to be served and the acceptable access and egress distances. Larger percentages would have led to more stops and a more complicated network, affecting the driving times of the different lines and increasing the number of vehicles required for the DRT service. On the other hand, the access and egress distances were considered to be conservative, especially for the high quality service which relied on access by bicycle. Brand et al. (2017) already showed that in practice, over 25 percent of bus passengers that access a high quality R-Net bus service by bike, travel further than the maximum distance used in these criteria. The fact that bus stops were often available withing the distances reduced the necessity to travel farther, indicating that even more passengers are willing to cover a larger access distance. Increasing the access and egress distances would have the opposite effect of increasing the service percentage. For the DRT service, more assumptions had to be made both for the access and egress distances and for the costs in timetable hours, because little data and information was available.

The data sets using for the area characteristics originated from different sources with varying quality. Because data of some destinations, such as MBO schools or job locations outside of Zuid-Holland, was not available, not all destinations were included in determining the stop locations and the bus lines. Large schools or job locations can attract a large number of passengers which were not included. Also, the importance of some destination types, especially for the leisure trip purpose, had to be assumed. By changing the importance, the stop locations and the resulting lines would have been different. Because the study area was located in a relatively urbanized region of the Netherlands, the results would have changed for other regions. Especially the effects of the DRT service are likely larger for more rural regions, because ethe usefulness of many regular fixed services decreases when the demand is lower.

During the designing phase, a large number of assumptions were made and many limitations existed, which were discussed in Section 9.2.1. For the evaluation and comparison, several limitations were mentioned in Section 8.2.1, which are in short mostly simplifications in order to reduce the computational time. Because these limitations were similar over all network designs, the resulting effects found by comparing the different designs were not affected. Furthermore, it was assumed that using a shared bicycle for the egress part was just as attractive as using a private bicycle for the access part. However, using a shared bicycle comes with a cost and uncertainties of whether a bicycle is available. In order for the shared bicycle to be as attractive as assumed in this report, the costs of the shared bicycle have to be as low as possible and travellers should be able to assume that a bicycle is available when the make a trip that relies on a shared bicycle.

9.2.3. Scientific Recommendations

From a scientific perspective several improvements can be made to this report. Some knowledge gaps were found which, when filled in, can be used for further improvements. First, a lack of knowledge existed about what acceptable criteria are for a DRT service, limiting the reliability of the results surrounding the DRT service. For future research, these gaps, especially for the access and egress distances and generalized costs, have to be filled in order to improve upon the conclusions for the DRT services. Also, improvements on the models can be made in future research in order to allow for more optimal results that can be compared better with an existing network. Improvements can be made to the stop location model in order to create a better insight in how much demand is served by placing a stop, which can be done by for example creating a heatmap instead of using a clustering algorithm. In the line creation model and the resulting evaluation improvements can be made in order to improve the efficiency of the calculations which would allow for greater access and egress distances to be included in the calculations. More insight in the effectiveness of individual line segments can also improve the transparency of the results. Finally, by using zones that are more uniform in size, biases towards lines to and from large zones can be reduced.

With these improvements, a similar study can be performed in order to confirm the findings by compare the results to an existing network. Because the study area that was used in this report, consisted of both rural and urban sections, the results might be different for more rural or more urban study areas. By using the same models and approaches as proposed by this report, these differences can be found. Furthermore, these models can also be applied to find the different effects of varying the criteria for access and egress distances, which were considered to be conservative in this report. By comparing different networks belonging to different criteria, the differences of the effectiveness of each practices can be found for different distances.

9.2.4. Societal Recommendations

In collaboration with the Province of Zuid-Holland, a parallel study was performed, that had an increase focus on the policy surrounding the implications of replacing slow, low frequent bus services by fast, high frequent services (Geurts et al., 2021). By using a similar stop locations model, it was found that loosening the criteria for the access and egress distances has large implications on the type of the service that can be provided. Similarly, according to this report, the use of shared bicycles increase the number of public transport trips as a result of increasing the criteria for the egress distances. In both studies, the existing criteria were loosened which allowed for stops to be placed along faster roads and lines to require less detours, resulting in large decreases in the driving time of the bus services. The time that was saved by these practices is used to provide the high quality service by increasing the frequency of the faster lines. Because of the high frequencies, the bicycle becomes an attractive access mode and when shared bicycles are offered, also as egress mode, making up for the greater access and egress modes. As a result of this, a large network of high quality services can be offered that provides in not only the patronage function, but also in a large part of the coverage function. The existing criteria for the access and egress distances, even for the high quality R-Net services, are too strict to offer such a network because too many detours are required. The remainder of the coverage function can be fulfilled by the use of DRT services, as long as shared bicycles are provided and the costs do not turn out to be more than 2,5 times as high as assumed in this report.

This report show the opportunities that arise when taking a step back from the slowly developed, existing bus network and looking without a bias of the existing networks at the locations where people live and where they want to go to. In Section 8.2.2, several examples of these opportunities were presented such as the use of the train station of Nieuw-Vennep as a larger transfer hub for passengers to Schiphol instead of operating multiple lines over the motorway without providing transfer options to any other destination. The use of this transfer hub introduces new connections between multiple towns and cities in and especially around Haarlemmermeer. An example of the effects of the access and egress criteria can be found in Noordwijkerhout where in the existing network two bus lines are operated snaking through the town. In all the new network designs, the fast provincial road was used that runs right through the middle of the town. In the existing network, the practice of moving bus lines from small roads to larger provincial roads was already shown to be highly effective in Zoeterwoude-Dorp. When the criteria are loosened, a similar opportunity exists for Noordwijkerhout and other towns and villages near comparable fast roads.

Furthermore, the models and approaches developed in this report can be used as a versatile tool by both transport authorities and transport companies in order to gain insight in the effects of the policy choices that are made. The weight assignment model and the stop location model can for example be used to analyse the percentage of homes and destinations that are served by a bus network or to find holes in the network that are not yet served by public transport. Using these models different networks can relatively quickly be developed showing the effects of different criteria.

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Appendix A: Effects of Zero-Emission Buses

By the year 2025, all new buses in the Netherlands have to be zero-emission and by 2030, all buses in operation have to be zero-emission (Rijkswaterstaat, n.d.). This can be achieved by using electric buses for which there are three main types of electric buses: hydrogen fuel cell, trolley and battery. Each of these three types have different characteristics and criteria. Hydrogen fuel cell buses have similar network criteria to diesel buses because of a similar range (Skiker & Dolman, 2017) and quick and easy refuelling. However, because of their inefficient energy usage and the limited number of expensive refuelling stations (MEED, 2019; Waterstofmagazine, 2021), it is unlikely that hydrogen fuel cell buses will be introduced on a large scale in the coming few years. Trolleybuses are also very expensive to operate because of all the extra required infrastructure, so they will also not be introduced on a large scale. Battery electric buses are much cheaper to introduce and therefore more likely to take the place of current diesel buses, but they have two main disadvantages: the limited range they can drive before they have to be recharged and the long recharging time. Within the battery electric buses there are two sub-groups of buses, each to reduce one of the main disadvantages.

First, are the opportunity charging buses which have a very limited range of only 50 kilometres, but a full battery charge can already be reached in 5 to 10 minutes of charging (Teoh et al., 2018). These buses can be used best for relatively short lines with charging infrastructure at larger stops. Plug-in buses with overnight charging are the opposite of opportunity charging buses, because the range is significantly longer at 300 kilometre, but reaching a full battery charge takes several hours. New technology is being developed rapidly for battery electric buses: Ebusco is expecting to bring a plug-in bus with a range of 500 kilometre on the market in 2021. Newly developed battery types can bring the range up to 1000 kilometre in the future (CROW, 2020).

According to CROW (2020), 61 percent of the buses in the concession area of ZHN drive less than 300 kilometre, 37% between 300 and 500 kilometre and 2% more than 500 kilometre. This means that with the increasing range of plug-in buses only 2% of the buses cannot be replaced one on one by battery electric buses. Therefore, range will not be an issue for 98% of the buses in ZHN. However, the charging infrastructure can make a difference, which is currently only located in the depot near Leiden Centraal and an opportunity charging station at train station De Vink. Most regional buses will likely be charged overnight, reducing the relevance of the location of charging stations. On the other hand, local buses are more likely to make use of opportunity charging, meaning that the routes that they can take, are more dependent on the locations of these charging stations. Because of the current lack of charging stations outside of De Vink and the likely increase in range of the battery electric buses, the use of zero-emission buses as a practice is not looked further into in the rest of this report. However, it should be noted that on the short term, the introduction of zero-emission buses can be eased by reducing the kilometres these buses have to drive on a daily basis, which results from the other practices mentioned in this report.

Appendix B: Comparison Straight Lines & Conventional Lines

Two comparisons were made between a bus line with a fast service and a bus line with an accessible service. The first comparison was made between two bus services between Noordwijk and Den Haag: line 90 with many stops in Katwijk and Wassenaar and line 385 with a more straight route through Katwijk and running over the motorway. The stops of these two lines are shown in Figure B.1 and the comparison for several sections is presented in Table B.1. The comparison shows that line 385 has a shorter travel time, largely as the result of the much shorter route through Katwijk. Between Katwijk and Den Haag line 385 is also slightly faster, because of the reduction in stops and by driving on the motorway. The number of passengers of line 90 is, with exception of the part in Noordwijk, either similar or higher than that of line 385. The difference at Noordwijk is explained by the fact that line 385 connects Noordwijk with train stations in Voorhout and Sassenheim, which are the closest train stations for Noordwijk. Reasons for why the slower line is more popular for the other sections, are the fact that line 385 operates only on weekdays as well as the fact the line 90 serves several tourist destinations, such as a theme park and the beaches of Katwijk and Noordwijk. When looking at only the passengers during the rush hours a different image occurs. During the rush hours line 385 is significantly more popular than line 90. In order to get a better image another comparison was made.

Figure B.1: Stops of line 90 (green), 385 (blue) and common stops (red) as of 2019 (OpenStreetMap contributors, n.d.).

Table B.1: Comparison of line 90 and line 385 based on the timetable of 2019 (Arriva, 2018).

		Line 90		**Line 385**	
		Southbound	Northbound	Southbound	Northbound
Van de Mortelstraat <-> Boekerslootlaan	*Number of stops*	9	9	6	6
	Distance [km]	4,9	4,8	4,0	3,9
	Average travel time [min]	12	10	10	10
	Average speed [km/h]	24,1	26,9	23,4	23,1
	Passengers Total	33.030		73.861	
	Passengers during rush hour	9.394		35.322	
Boekerslootlaan <-> Raadhuis	*Number of stops*	17	18	4	4
	Distance [km]	9,0	9,1	4,5	4,6
	Average travel time [min]	18	19	9	8
	Average speed [km/h]	28,9	28,0	29,4	30,9
	Passengers Total	54.697		38.554	
	Passengers during rush hour	19.642		25.978	
Raadhuis <-> Willem Witsenplein	*Number of stops*	17	18	7	6
	Distance [km]	16,1	17,0	16,7	17,0
	Average travel time [min]	31	30	29	28
	Average speed [km/h]	30,5	33,5	33,8	35,7
	Passengers Total	105.720		72.272	
	Passengers during rush hour	33.075		46.579	
Willem Witsenplein <-> Den Haag Centraal	*Number of stops*	2	2	2	2
	Distance [km]	2,0	2,2	2,0	2,2
	Average travel time [min]	6	5	6	6
	Average speed [km/h]	18,7	26,4	18,6	20,1
	Passengers Total	104.563		109.602	
	Passengers during rush hour	30.670		70.240	

For the other comparison, two bus services between Roelofarendsveen and Leiden were used: line 365 with a much more direct route and line 56 with several additional stops in Rijpwetering, Oude Ade, Leiderdorp and the city centre of Leiden, as can be seen in Figure B.2. Line 365 connects further to Schiphol and some destinations near Hoofddorp, while line 56 connects further to Leimuiden. Both lines have a similar frequency as both run twice per hour during weekdays and once per hour during weekends.

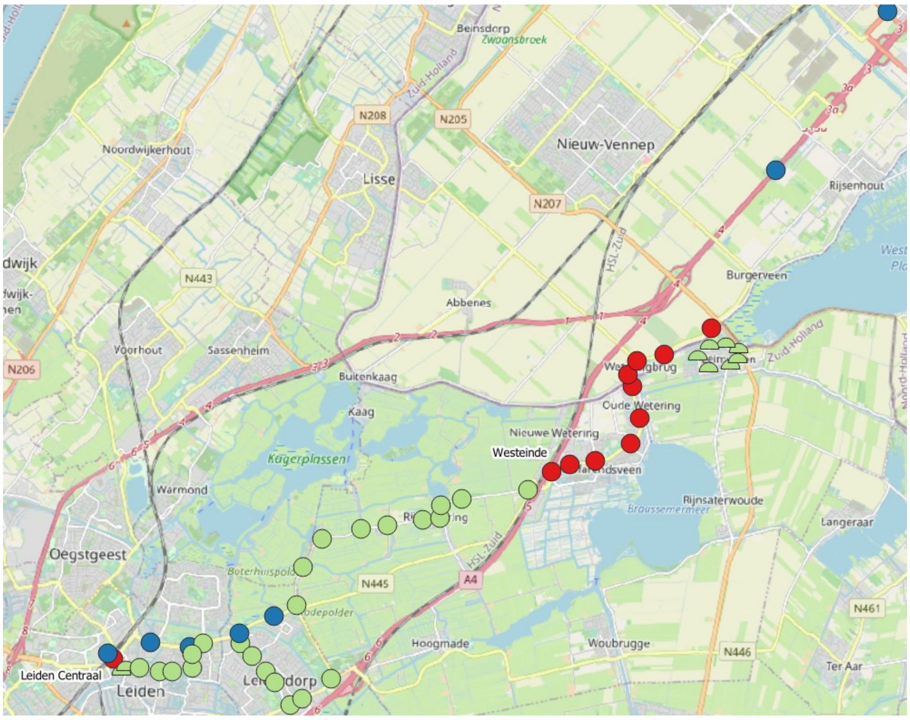

Figure B.2: Stops of line 56 (green), 365 (blue) and common stops (red) as of 2019 (OpenStreetMap contributors, n.d.).

Table B.2 shows that line 365 is approximately 10 minutes faster between Leiden Centraal and the first common stop (Westeinde) in Roelofarendsveen. Line 365 also attracts around 2,5 times more passengers at the common stops. However, it can be argued that this is because of the better connections on the other side of Roelofarendsveen, as line 365 connects further to Schiphol while line 56 only connects further to Leimuiden where a transfer to Alphen aan den Rijn can be made. In order to investigate this, an assumption was made stating that all passengers at east side are travelling either to or from the common section with no internal passengers in Leimuiden or Schiphol. Because this is not very realistic because there are also passengers from Leiden en Leiderdorp to these destinations as well as passengers between Hoofddorp and Schiphol, this assumption is an underestimation of the number of passengers using line 365 towards Leiden. Even with this underestimation, there are still 43671 passengers left in line 365 and only 29736 in line 56, meaning that line 365 still attracts almost 50 percent more passengers while serving less destinations within a short distance.

Table B.2: Comparison of line 56 and line 365 based on the timetable of 2019 (Arriva, 2018).

	Line 56 Westbound	**Line 56 Eastbound**	**Line 365 Both directions**
Number of stops	23	25	5
Distance [km]	15,7	16,1	11,6
Average travel time [min]	34	31	23
Average speed [km/h]	27,1	30,9	29,8
Total Passengers at Leiden Centraal	103.852		110.891
Total Passengers at the Leiden side of Westeinde (excluding Leiden Centraal)	158.437		46.583
Total Passengers at the common section	52.015		135.253
Total Passengers at the Leimuiden/Schiphol side	22.279		91.583

Appendix C: Frequencies of Existing R-Net Bus Services

In order to find what services are currently common for R-Net bus services, the daily frequencies of existing R-Net bus services were analysed by determining the number of buses that were operated between the first and the last service as well as the time between the first and the last service. Because many of the bus lines had segments at the ends of the routes with a lower frequency, only the segments with the highest frequencies were considered in this analysis. Furthermore, bus services that operated only during rush hours or on weekdays were not included. Also, one line was excluded because it was temporarily not operated because of Covid. Night services were also not considered. The resulting overview of the remaining services is presented in Table C.1. The average of all these lines is found in Table C.2.

Table C.1: Average frequencies of R-Net bus services and their average hours in operating service per day for the line sections with the highest frequency (allGo, n.d.; Arriva, n.d.-a; Connexxion, n.d.; EBS, n.d.-a, n.d.-b, n.d.-c; GVB, n.d.; Qbuzz, n.d.; RET, n.d.).

Line number	**Concession**	**Average frequency per hour**				**Average hours in operating service**
		Mon – Fri	**Sat**	**Sun**	**Average**	
300	Amstelland-Meerlanden	8,51	6,02	5,96	**7,79**	19,62
397	Amstelland-Meerlanden	6,92	5,63	4,13	**6,34**	19,37
340	Amstelland-Meerlanden	6,33	3,53	3,42	**5,51**	18,39
369	Amsterdam	5,85	4,51	4,05	**5,40**	19,67
356	Amstelland-Meerlanden	5,54	3,62	3,54	**4,98**	18,42
346	Amstelland-Meerlanden	5,74	3,61	2,04	**4,91**	18,14
400	Zuid-Holland Noord	5,56	3,00	2,06	**4,70**	19,46
385	Haarlem-IJmond	4,96	3,90	3,83	**4,65**	18,83
341	Amstelland-Meerlanden	5,04	3,65	2,99	**4,55**	18,69
403	Voorne-Putten & Rozenburg	4,92	3,12	2,05	**4,26**	18,56
404	Voorne-Putten & Rozenburg	4,24	3,32	2,77	**3,90**	18,76
320	Gooi & Vechtstreek	4,33	3,29	2,07	**3,86**	19,26
314	Waterland	4,35	3,17	2,06	**3,85**	19,73
315	Waterland	4,10	3,29	2,06	**3,69**	19,23
382	Haarlem-IJmond	4,18	2,06	2,06	**3,58**	18,18
308	Waterland	3,87	3,46	2,06	**3,55**	19,10
304	Waterland	3,85	3,51	2,05	**3,55**	19,37
301	Waterland	3,85	3,46	2,06	**3,54**	19,39
306	Waterland	3,87	3,30	2,06	**3,53**	19,12
305	Waterland	3,84	3,24	2,06	**3,50**	19,23
316	Waterland	3,64	3,18	3,00	**3,48**	18,59
319	Waterland	3,76	3,47	2,06	**3,47**	19,33
307	Waterland	3,73	3,35	2,06	**3,44**	19,23
312	Waterland	3,49	3,19	3,20	**3,40**	19,10
170	Rotterdam	3,89	2,06	2,07	**3,37**	17,90
470	Zuid-Holland Noord	3,81	1,94	1,94	**3,28**	17,05
391	Zaanstreek	3,40	3,03	2,87	**3,27**	17,87
392	Zaanstreek	3,48	2,93	2,07	**3,20**	18,28
416	Drechtsteden, Molenlanden & Gorinchem	3,53	2,67	2,06	**3,19**	18,16
394	Zaanstreek	3,42	3,02	2,20	**3,19**	18,32
173	Rotterdam	3,59	2,08	2,10	**3,16**	18,20
497	Zuid-Holland Noord	3,56	2,06	2,06	**3,13**	18,54
347	Amstelland-Meerlanden	3,40	2,76	2,06	**3,12**	19,41
358	Amstelland-Meerlanden	3,38	2,82	2,07	**3,11**	18,63
357	Amstelland-Meerlanden	3,37	2,89	2,06	**3,11**	19,05
348	Amstelland-Meerlanden	3,37	2,74	2,07	**3,09**	17,55
455	Haaglanden	3,50	2,06	2,06	**3,09**	17,96
456	Haaglanden	3,48	2,04	2,05	**3,07**	18,33
488	Drechtsteden, Molenlanden & Gorinchem	3,47	2,06	2,06	**3,07**	18,29

489	Drechtsteden, Molenlanden & Gorinchem	3,46	2,06	2,06	**3,06**	17,33
491	Drechtsteden, Molenlanden & Gorinchem	3,45	2,06	2,06	**3,05**	17,36
436	Hoeksche Waard – Goeree-Overflakkee	3,38	1,08	1,07	**2,72**	17,60
410	Zuid-Holland Noord	2,97	2,06	2,06	**2,71**	18,45
430	Zuid-Holland Noord	2,89	2,18	1,94	**2,65**	18,53
431	Zuid-Holland Noord	2,88	2,05	2,06	**2,64**	18,82
322	Almere	2,59	1,70	1,14	**2,26**	20,24
328	Almere	2,55	1,67	1,06	**2,21**	17,90
327	Almere	2,40	1,69	1,06	**2,11**	18,38

Table C.2: Average frequencies and average hours in service.

Average frequency per hour				**Average hours in operating service**
Mon – Fri	**Sat**	**Sun**	**Average**	
4,04	2,91	2,33	3,63	18,64

Appendix D: Hospital Egress Distances

In order to find acceptable egress distances for both high quality bus services and regular bus services, a small analysis was done. For the hospitals in the study area and some hospitals in the surrounding area, the egress distances were estimated using the Google Maps route planner for walking. The walking routes were calculated between the main entrance of the hospital and the closest platform for each service level. In some cases, a rough estimation was made to create a shorter route, because not all possible walking links were included in Google Maps. For longer walking distances the estimations of Google Maps became more rough, for example walking distances over 300 metres were rounded to the nearest number divisible by 50. For this report, these rough estimations were good enough because they were used in an educated guess what distance could be seen as acceptable. As shown in Table D.1, most high quality service stops were less than 500 metres from the main entrance of the hospital. Even though there are some hospitals where this distance is larger, it should not be directly assumed that these larger distances were acceptable. Therefore, 500 metres was a more safe estimate to be acceptable. In a similar fashion, a distance for the regular services was estimated to be a 200 metres at most. Although only one hospital had a longer distance of 300 metres, 200 metres was a more safe estimate. For both the high quality service as the regular service a shorter distance was preferable where possible.

Table D.1: Hospitals and the egress distance for each level of service.

Hospital	**High quality service stop**	**Regular service stop**	**Egress distance high quality service (in metres)**	**Egress distance regular service (in metres)**
Alrijne Leiden	Leiden, Posthof*	Leiden, Alrijne Ziekenhuis	500	35
Alrijne Leiderdorp	Leiderdorp, Ziekenhuis**	Leiderdorp, Ziekenhuis**	350	150
Alrijne Alphen a/d Rijn	Alphen a/d Rijn, Ziekenhuis	Alphen a/d Rijn, Ziekenhuis hoofdingang	600	100
LUMC	Leiden Centraal Westzijde	Leiden Centraal Westzijde	300	300
Spaarne Gasthuis Haarlem Zuid	Haarlem, Europaweg	Haarlem, Boerhavelaan / Spaarne Gasthuis	500	200
Spaarne Gasthuis Hoofddorp	Hoofddorp, Spaarne Gasthuis**	Hoofddorp, Spaarne Gasthuis**	15	65
LangeLand Ziekenhuis	De Leyens***	Zoetermeer, LangeLand Ziekenhuis	650	180

* Not a high quality service stop, but a stop with many services. No high quality service stop nearby

** Stop with multiple platform, distances based on closest platform for each service

*** Not a bus stop, but a light rail station

Appendix E: Visualization of All Origins and Destinations

In this appendix, the data used in Section 6.1 is visualized.

Figure E.1: Concentrations of inhabitants (OpenStreetMap contributors, n.d.; CBS, 2021a).

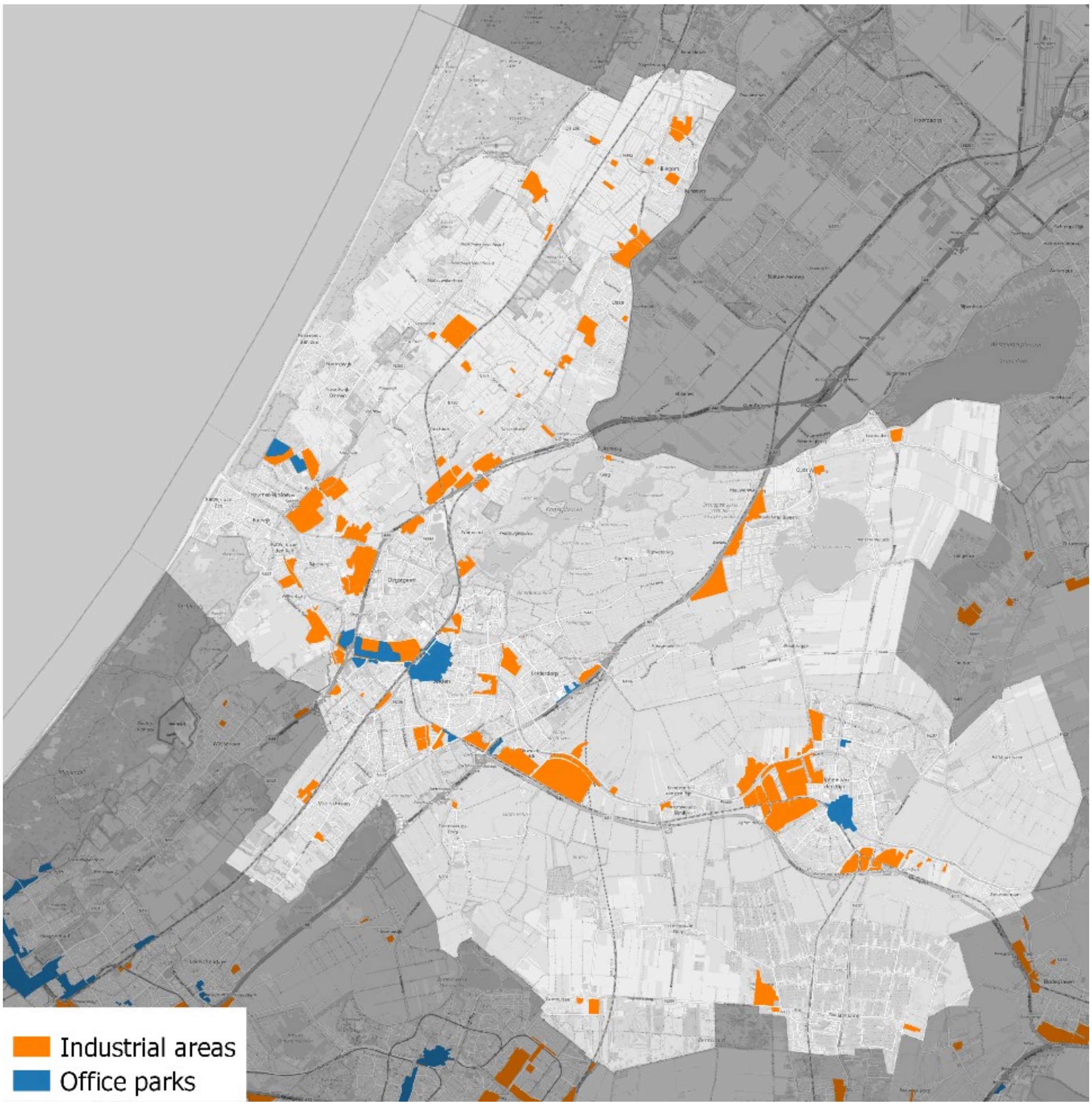

Figure E.2: Industrial areas and office parks in the study area (OpenStreetMap contributors, n.d.; Provincie Zuid-Holland, 2019; Provincie Zuid-Holland, 2020b).

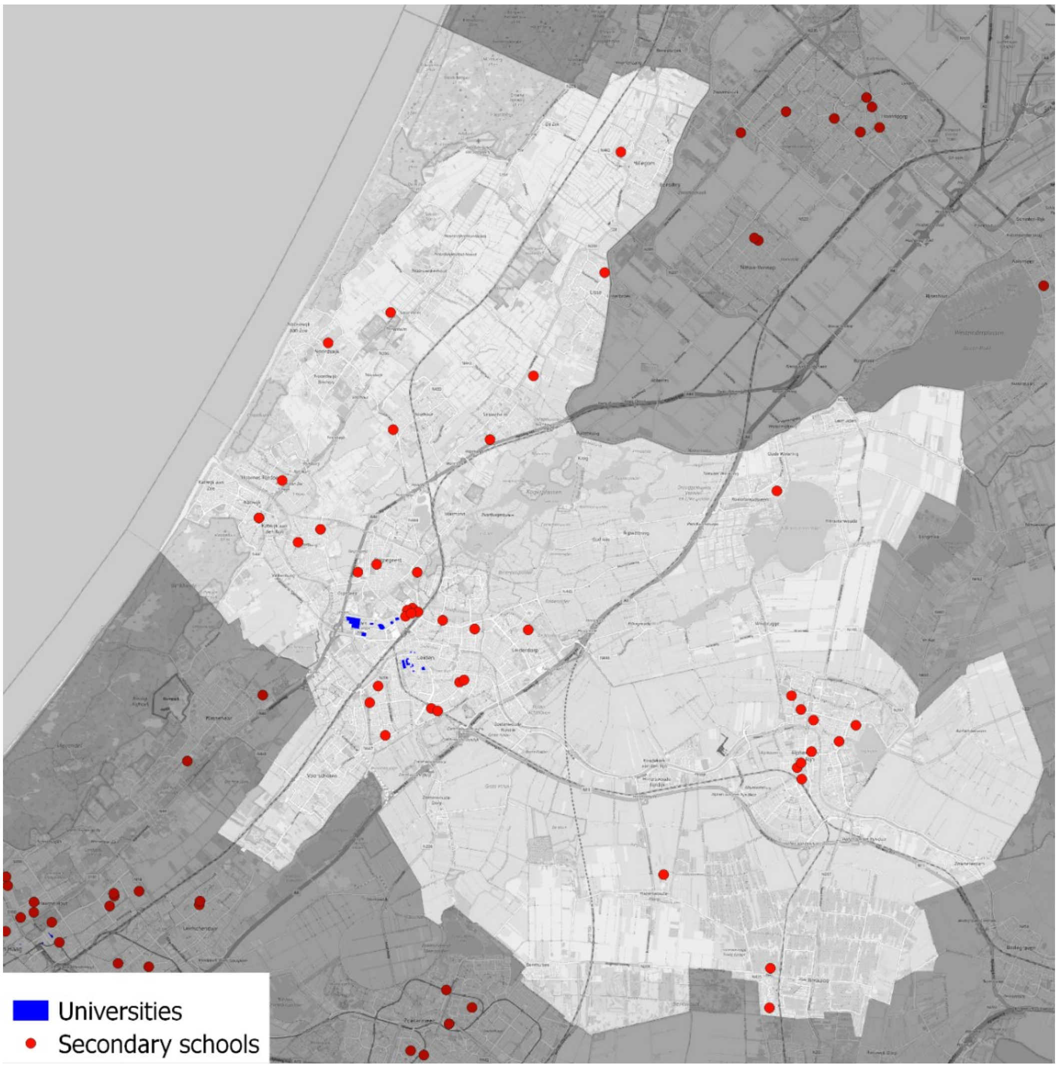

Figure E.3: Education locations (OpenStreetMap contributors, n.d.).

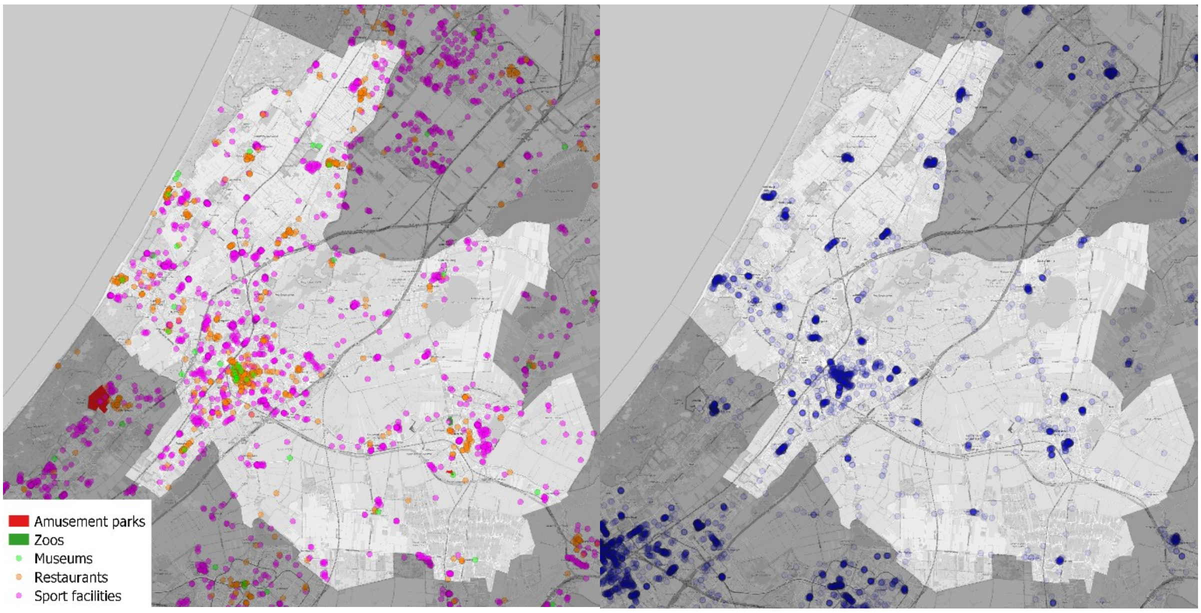

Figure E.4: Leisure destinations (left) and shops (right) (OpenStreetMap contributors, n.d.).

Figure E.5: Service destinations (OpenStreetMap contributors, n.d.).