Multimodal transport network with the bicycle as core

Master Thesis

Roland Claessens

TU Delft

SWECO

Multimodal transport network with the bicycle as core

Master Thesis

By

Roland J.I. Claessens

To obtain MSC degree Transport & Planning
at the Delft University of Technology,
to be defended publicly on Thursday 3 October 2019 at 13:00 PM.

Student number:	4160452	
Supervisor:	Prof. dr. ir. B. van Arem,	TU Delft
Thesis committee:	dr. ir. N. van Oort,	TU Delft
	dr. J.A. Annema,	TU Delft
	R. van Hout	Sweco

An electronic version of this thesis is available at http://repository.tudelft.nl/.

Preface

Met de afronding van het thesisrapport komt er een einde aan zowel deze thesis als mijn studie. Tijdens beide periodes zijn er vele hoogte- en dieptepunten geweest. Desondanks is heb mij gelukt om Uiteindelijk de Master Transport & Planning aan de TU Delft te voltooien, iets wat veel mensen niet zou hebben verwacht.
Dat ik dit heb bereikt, heb ik aan veel mensen te danken. Allereerst wil ik Bart van Arem, Jan Anne Annema, Niels van Oort en Rob van Hout hartelijk bedanken voor het begeleiden van mijn thesis. Dit is niet altijd even makkelijk geweest. Door mijn, van nature, redelijk chaotische aanpak en denkwijze was het voor jullie soms erg lastig om te begrijpen waar ik precies heen wilde en de methodiek erachter. Desondanks hadden jullie het vertrouwen dat het uiteindelijk goed zou komen.
Daarnaast wil ik Sweco en nogmaals Rob van Hout bedanken voor de fijne stageperiode bij jullie. Het was een leerzame periode voor mij, en ik had het erg naar mijn zin.

Verder wil ik mijn familie bedanken voor de steun. Nathalie & Valerie, Jullie waren er altijd voor mij wanneer het allemaal even wat minder ging. Jaap & Anita, zonder jullie was ik niet eens op de TU Delft gekomen. Terwijl anderen meerdere malen zeiden dat het niveau te hoog zou zijn, geloofden jullie wel in mij. Ook heeft Jaap zonder bezwaar altijd de taal en grammatica van dit rapport willen controleren. Bedankt daarvoor.

Lieve opa,

Voor jou komt de afronding van het thesisrapport en mijn afstuderen net te laat. Je was erg trots op dat ik studeerde aan de TU Delft en toonde altijd veel interesse in mijn studie. Toen ik begon aan mijn Master Transport & Planning begon ook jij mobiliteit interessant te vinden. Ik had dan ook graag een exemplaar van dit rapport aan jou overhandigd. Helaas is dit niet meer mogelijk. Het geeft mij zeer veel verdriet dat jij dit allemaal niet meer meemaakt.

Rust zacht

Roland Claessens
Delft, 22 September 2019

SUMMARY

When using the transit for travelling to a certain destination, most travellers are first travelling (access trip) to a bus/tram/metro (BTM) stop or a train station. This is often done by walking. Also in the last part of the trip (egress trip) travellers often walk. As walking is generally quite slow (usually 3 to 5 km/h), most travellers do not want to walk large distances to or from a BTM stop or train station. To make the transit network accessible for all these travellers, a dense transit network is needed.
Another possibility is to use multimodal trips with the bicycle as access- and egress trip mode. As the travel speed on a bicycle is much higher than walking, the access/egress trip travel distance become larger with the same travel time. With a larger access- and egress trip distance willingness, a coarser transit network might be possible. In a coarser transit network less stops and transit lines are needed. This can save travel time for travellers and operational costs. The operational costs savings can be used to increase the frequency of a service line to lower the average waiting time. With the cooperation between the bicycle and transit, the bicycle- and transit infrastructure network can be merged into one multimodal infrastructure network.

This thesis "Multimodal network with the bicycle as core" is made to know more about the effects of using the bicycle as access- and egress mode in a multimodal trip on aspects like travel time, modal split and operational costs. With bicycle as core, the bicycle use becomes central in the multimodal network. Furthermore, the transit routes and the locations of stops and stations are adapted to the bicycle use. This can be seen as a bottom-up approach.
The main research question of this study is: *To what extent does a multimodal passenger transport network with the bicycle as core reduce the total travel time for most travellers and increase the modal split for (multimodal) transit trips, without high investment- and operational cost.*

To obtain existing information, a literature study is done focussing on three aspects. First, information about the travel distance willingness of cyclists called 'catchment radius' is obtained. These catchment radius values indicate how far travellers are willing to cycle to or from a BTM stop, train station and P+R or from door-to-door. These values can be used to determine suitable locations for BTM stops and train stations.
Also the trip preferences of the traveller during a multimodal trip are studied to determine the attractiveness of a trip from travellers perspective. These preferences are converted into travel time multipliers and -penalties. With these multipliers and penalties, the 'experienced travel time' of the traveller during a trip can be calculated.
Last, information about general outlines of multimodal network and (multilevel) transit services are obtained. This includes information about possible outlines of a (multimodal) network, network hierarchy, and applying multilevel transit services.

The literature study indicates that the catchment radius is dependable of the bicycle type. While cyclists on a regular bicycle had an average trip distance of approximately 3,5 km, E-bike users travelled on average around the 5 km. Also for access and egress trips to a BTM stop, train station, and P+R, different catchment radius values were found. Especially for the access trips to a BTM stop, research papers showed a wide range of different catchment radius values. It appeared that the quality of the BTM line influences the radius value as cyclists are willing to travel further to a BTM service line with a higher frequency and operational speed. Based on the results of the studied papers, catchment radius values for this thesis are determined as shown in Table 1. As the catchment radius value for access trips to a BTM stop is dependable of the quality of the BTM service lines, a range instead of one value is stated. Furthermore, it is assumed that the regular bicycle and E-bike are used for door-to-door and access trips, while the shared-bike is used for egress trips.

Table 1 Catchment radius values

	BTM		Train		P+R	Door-to-Door
	Access	Egress	Access	Egress	Egress	
Regular bicycle	1000-2000 m	-	2500 m	-	-	3500 m
E-bike	1400-2900 m	-	3600 m	-	-	5000 m
Shared-bike	-	1500 m	-	2000 m	1500 m	-

Furthermore, the literature study showed that the traveller has a high discomfort while walking to or waiting for a transit vehicle. They also dislike transferring, with a travel time penalty of 5,5 min per transfer between transit modes. It also appeared that the traveller has a higher preference for cycling than the train and BTM. the final travel time multipliers and -penalties are shown in Table 2.

Table 2 Travel time multipliers and -penalties

	Value
Walking time	1,75
Waiting time	1,75
Cycling time	0,75
In-vehicle time BTM low level	1,2
In-vehicle time BTM high level	1,2
In-vehicle time Train	1
Transfer penalty	5,5 min

The literature study on multimodal networks and -service outlines indicated that a distance scale factor of 3 between two hierarchical transit lines should be applied. So, if the stop spacing of a low-level transit line is 1000 m, the spacing between two stops at a high-level transit service should be 3000 m. For the operational speed, a scale factor of 1,67 is most suitable. When applying a multi-level transit service system, three outlines are realistic: `Express', `Trunk-Feeder' and `Zone'. Examples of these services combined with a bicycle access trip are shown in Figure 1.

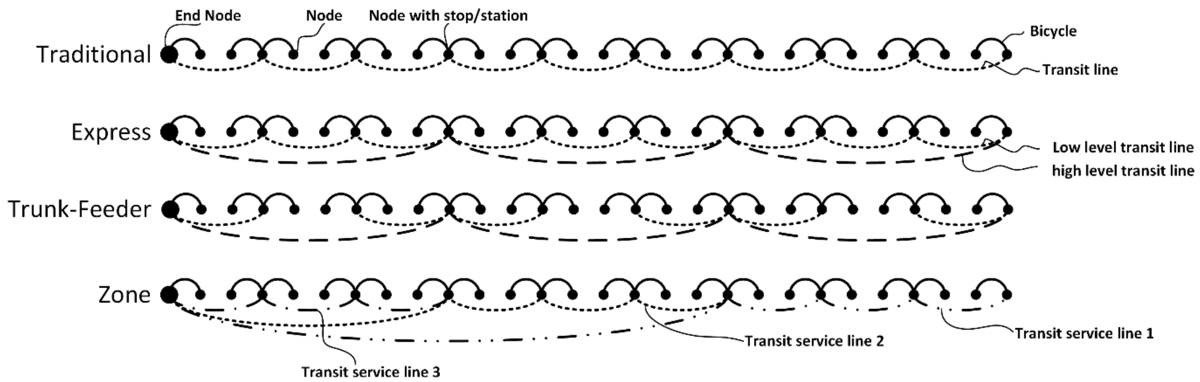


Figure 1 Multi-level transit services

Based on the findings of the literature study, a start is made on studying the effects of bicycle catchment radius values and (multi-level) transit services on the (experienced) total travel time and (experienced) connection quality (min/km). To do this, two scenarios called 'Corridor' and '2D Corridor', are made. The first scenario consists of a one-dimensional corridor with dozens of nodes. The second uses a two-dimensional plane. In these two scenarios, multiple different combinations of bicycle catchment radius values and (multi-level) BTM services are made. Next step is to calculate the (experienced) travel time and -connection quality between each origin and destination (OD). Based on the calculation results, two combinations with the most potential in terms of travel time improvement and cost are chosen and applied in the third scenario called "Mobili-City. In this scenario, multimodal networks with the bicycle as core are designed and simulated for a fictive city. During the design, a self-made design strategy is used. In this scenario, the investment- and operational costs are also calculated. Based on the calculation results of the third scenario, a first indication about the effects of a multimodal network with the bicycle as core can be made. Furthermore, first suitable applications are determined.

The results of the first two scenarios showed that using different bicycle catchment radius values had a large impact on the (experienced) travel time and -connection quality. For travellers cycling to a BTM stop in the opposite direction of their destination (travelling first ‘upstream’), a catchment radius larger than 1000 m has a high negative impact on the travel time and connection quality. When travelling ‘upstream’, it creates extra travel distance in a transit vehicle. If the BTM stop is in the same direction as the destination (downstream), a catchment radius of 2000 m still had a positive impact on the travel time compared to a walking-BTM combination. Therefore, applying an ‘asymmetric’ bicycle catchment radius for BTM stops can be interesting to apply. For travellers cycling ‘upstream’ to a BTM stop the catchment radius is 1000 m, and 2000 m when cycling ‘downstream’ to the stop. Eventually, applying an asymmetric catchment radius created the most (experienced) travel time improvement. However, the difference with a circular 1000 m catchment radius is small.
The results also showed large differences between the applications of different (multi-level) transit services. Overall, it appeared that applying an Express or Trunk-Feeder BTM service system created mixed results. While the travel time results were good, they scored much worse with the experienced travel time compared to the traditional BTM service (vehicle stops at every stop/station). Only a zone based BTM service system created a significant improvement compared to the traditional services. However, applying a zone-based service system is only useful with many stops along the transit line. With only a few stops, the gains are minimal. Furthermore, if there are multiple zones, stops or stations with a high traveller demand, a zone-based system is less suitable to apply.
Based on the results of the first two scenarios, it is concluded that two bicycle catchment radius values combined with a traditional BTM service system are suitable to apply. The first one is a circular catch-ment area with a radius of 1000 m. The second one is an asymmetric area with a radius of 1000 m for travellers cycling ‘upstream’ to a BTM stop and 2000 m for cycling ‘downstream’.
In the Mobili-City scenario, first multimodal networks with the bicycle as core are designed. As the previous two scenarios indicated two suitable bicycle catchment areas, these two alternatives are used: The first applies the 1000 bicycle catchment radius, and the second the asymmetric. To design a multimodal network with the bicycle as core, a self-made design strategy is used. The general outline of this strategy is shown in Figure 2. In Figure 3, the designs of both alternatives are shown. For both alternatives, the (experienced) travel time, -connection quality, investment-, and operational costs are calculated.

Figure 2 General outline design strategy

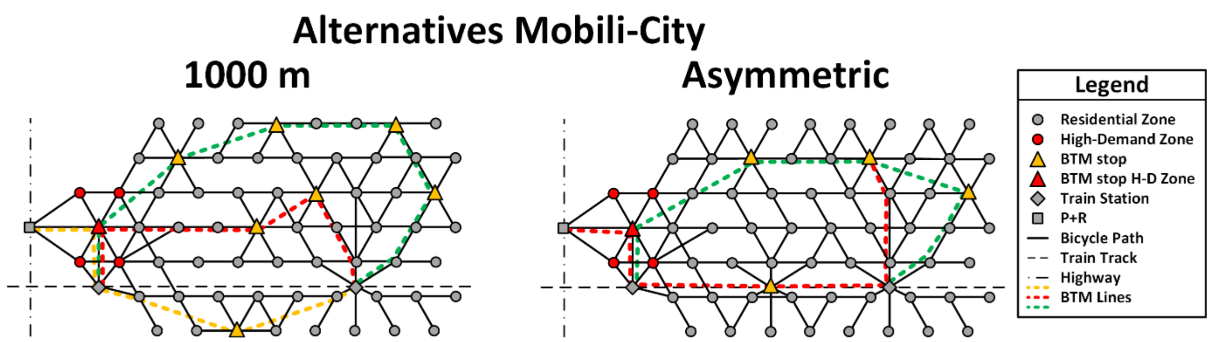


Figure 3 Alternatives Mobili-City

In terms of (experienced) travel time and -connection quality, the difference between the two alternatives are very small. But the Asymmetric alternative has a much lower investment- and operational cost. Main reason is the need of two BTM lines instead of three in the 1000 m alternative. Therefore, it is more suitable to use an asymmetric bicycle catchment area for BTM stops.
Based on the results of all three scenarios, a preliminary conclusion about the effects of a multimodal network with the bicycle as core can be concluded. First, the results of scenario 1 and 2 show that a bicycle-transit combination has a much lower (experienced) travel time and a better connection quality compared to a walking-transit combination. Furthermore, scenario 2 showed that the operational costs of bicycle-transit combination are much lower. The results from all scenarios indicate that an asymmetric bicycle catchment area (1000-2000 m) should be applied, instead of a circular area for BTM stops. Furthermore, a traditional BTM service system is more suitable, instead of a multi-level BTM service.

To know more about the effects of a multimodal network with the bicycle as core on travel time improvement and modal split for an existing area, a case study called Utrecht Science Park (USP) is done. In this case study, a multimodal network with the bicycle as core is designed for the USP and region east of the city Utrecht in the year 2030. The goal of this study is to test if a multimodal network with the bicycle as core is suitable to lower the total travel time of multimodal trips and decrease the car-use for trips to the USP. By using the self-made design strategy, two alternatives of multimodal networks with the bicycle as core are designed called: Basic and Plus. These designed networks consist of (main) bicycle routes, multiple BTM stops, new train stations and BTM service lines. In Figure 4, the designs of both alternatives are shown. In the Plus alternative, extra feeder stations are created to unburden Utrecht CS and the Uithoflijn. During this case study, these alternatives are compared with the zero alternative. To simulate the travel trips, the Vervoers Regio Utrecht (VRU) model -running on Omnitrans- is used.

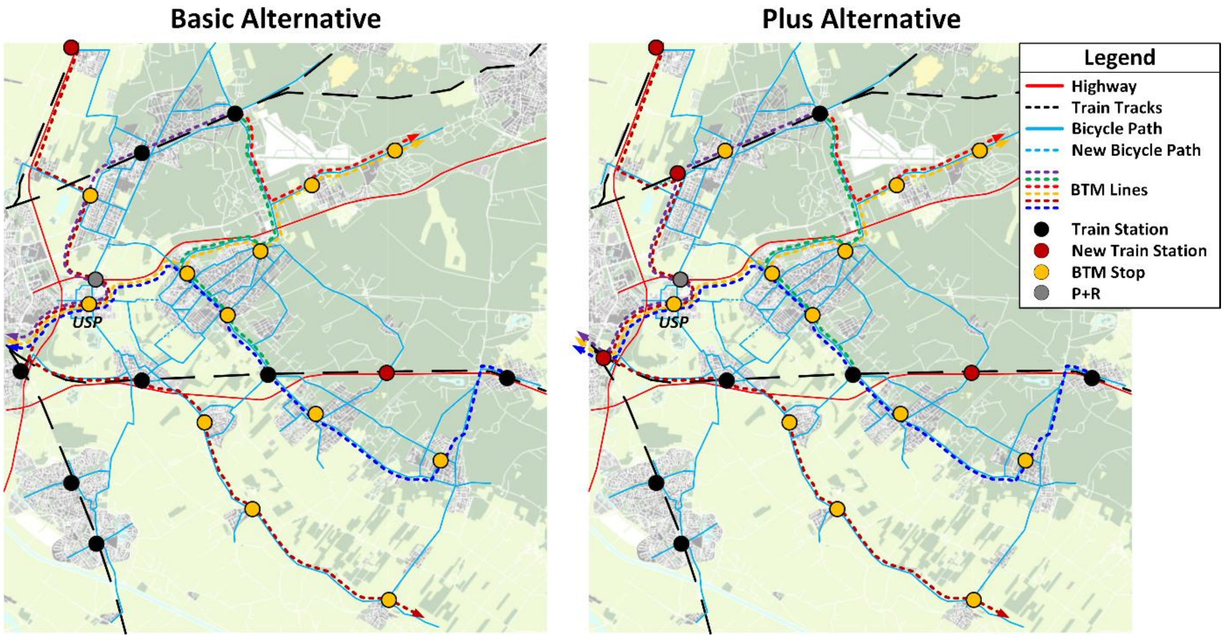


Figure 4 Multimodal network alternatives case study

In the zero alternative, a bicycle-transit trip combination to the USP is always more than two times slower than travelling by car (on average 2,8 times). In some occasions, it was even more than four times slower. With both Basic- and Plus alternative, the difference with car use has become much smaller. On average, the bicycle-transit trip combination is in the basic alternative only 1,7 times slower than the car trip. With the Plus alternative, it is 1,6 times slower on average. Furthermore, these multimodal trips are rarely more than two times slower than the car. These values show that the travel time decreases significantly when applying a multimodal network with the bicycle as core.

During the morning rush hours (period of two hours), more than 39.000 people travel to the USP area. In the zero alternative, more than 27.000 (70 %) of these travellers use a transit mode (including multimodal) and 7700 (20 %) a car to travel to the USP. With both Basic- and Plus alternative, the modal split changed to 29.000 (74 %) (multimodal) transit trips and 6400 (16 %) car trips to the USP during the morning rush hours. By applying the multimodal network with the bicycle as core, at least 1300 car users choose for a different mode when travelling to the USP.
In terms of travel time and modal split, the differences between the Basic- and Plus alternative are not significant. However, an extra goal for the Plus alternative is to unburden Utrecht CS and the Uithoflijn. In the basic alternative, more than 10.000 travellers depart with the Uithoflijn from Utrecht CS. In the Plus alternative, this has decreased to 8100. As the total number of transit users remains more or less the same, it means that 2000 travellers use a different transit route.
Overall, the case study has shown that with a multimodal network with the bicycle as core, the travel time will decrease significantly. Due to the travel time decrease, more travellers will use a bicycle-transit trip mode combination and therefore car-use decreases.

Conclusion
This thesis focused on the design of a multimodal passenger network with the bicycle as core and its effects on the total (experienced) travel time, modal split and (operational) costs. The study showed that an asymmetric bicycle catchment area for BTM stops was most effective in terms of total (experienced) travel time and operational cost in comparison to a circular catchment area. When travellers have to cycle to a BTM stop in the opposite direction of their destination, the catchment radius should be 1000 m. If the BTM stop is in the same direction, a radius of 2000 can be applied. Combined with a traditional BTM service system, a bicycle-transit combination has a much lower (experienced) travel time and operational cost than a walk-transit combination. In the case study, applying a multimodal network with the bicycle as core showed, besides a travel time decrease, a decrease of car-use and an increase of (multimodal) transit trips.

With regard to the main research question, this thesis has shown that a multimodal network with the bicycle as core can create a large decrease of the total travel time when using a bicycle-transit trip combination. Due to the travel time decrease, more travellers will use a (multimodal) transit trip, instead of the car. Furthermore, this multimodal network can be applied with a lower operational cost compared to a network based of walking as access and egress from/to transit modes. Estimating the investment costs is trickier, as this depends greatly on the decision to implement a bus/BRT, tram/light-rail, or a metro as mode for BTM services.
While a lot of research is still needed, this thesis has shown the potential of applying the bicycle as core in a multimodal network. It can be used to (indirectly) decrease the car-use while also improving the accessibility of a region. These advantages fit into the goals of the Dutch government to improve sustainability and accessibility in the Netherlands.

1 TABLE OF CONTENTS

1 INTRODUCTION

When using transit for travelling to a destination, it is (normally) necessary to travel first to a bus/tram/metro (BTM) stop or a train station. For BTM stops, it is often assumed that travellers walk to the stop. With a walking distance willingness of around 400 m (Rijsman, 2018), a low stop- and line spacing value in the BTM network is needed to make it accessible for all travellers. As it is not realistic to do the same with a train network, the BTM service lines often function as a feeder for the train network. However , it is also possible to use the bicycle as travel mode for travelling to the BTM stops and train stations.

Figure 5 shows how, in general, a transit trip is structured. It consists of three 'legs' called: access trip, main trip, and egress trip (van Nes R. , 2002). First, an access trip to a transit stop or station is made, where traveller transfers to a transit mode for the main trip. During the main trip, traveller may transfer to other transit modes. The egress trip is used to travel from the transit stop or -station to the destination. Both access- and egress trips can be done by walking or using the bicycle. While not shown in the figure, it is also possible to use the bicycle as access and walking as egress (and other way around).

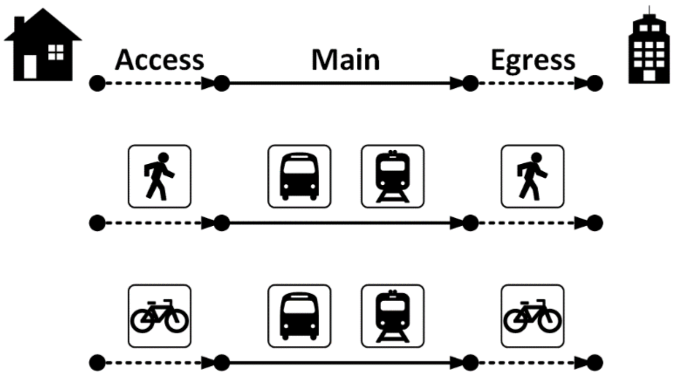


Figure 5 Outline transit trips

With an average travel speed of 12,3 km/h (KiM, 2017) cyclists are travelling much faster than walkers (around 4 km/h). Due to the higher travel speed, the 'catchment area' of cyclists is much larger. The catchment area shows the walk or cycling range of a traveller, determined by the 'catchment radius'. For the effect of using a larger catchment area, see Figure 6. In this sketch, catchment areas of transit stops are drawn. In this example walkers have a catchment radius of 1 and cyclist a radius of 2. It can be seen that applying a larger catchment area results into fewer transit stops and lines, while the total area covered by the catchment area remains the same. Fewer transit stops means less travel time loss (dwell time, decelerating). With fewer transit lines, less transit vehicles are needed, or they can be allocated to the remaining service lines.

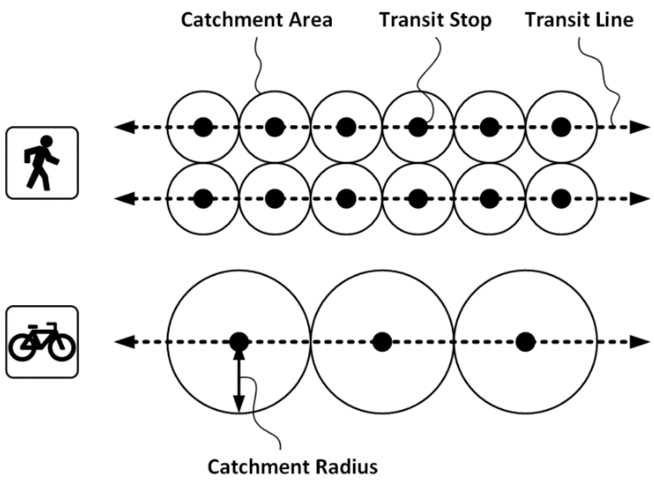


Figure 6 Sketch catchment areas

The bicycle-transit combination is an example of multimodal transport. Multimodal transport is defined as using multiple different travel modes (car, train, bicycle, etcetera) to travel from A to B. When the traveller is using one mode type, it is considered as an unimodal trip. Walking is not considered as part of multimodal transport, as otherwise, almost every trip can be considered as a multimodal trip. Using two different transit modes during a trip (for instance bus and train) is also considered as a multimodal trip.

The multimodal trips are made within a multimodal network. These multimodal networks have often a hierarchical outline (van Nes R. , 2002). An example of a hierarchical network is shown in Figure 7. The low-level network operates often at a local/city level and has a dense network to create a high accessibility. Due to the dense network, the operational speed is often low. Besides creating accessibility, the low-level network also feeds the high-level network. The high-level network operates more at a regional/national level with a coarse network. Furthermore, its operational speed is much higher. Using the bicycle instead of walking as access and egress mode could have a large impact on the hierarchical outline of the multimodal network. For instance, the bicycle can replace the bus for operations at a low network level. Another possible option is to make both low- and high-level network less dense.

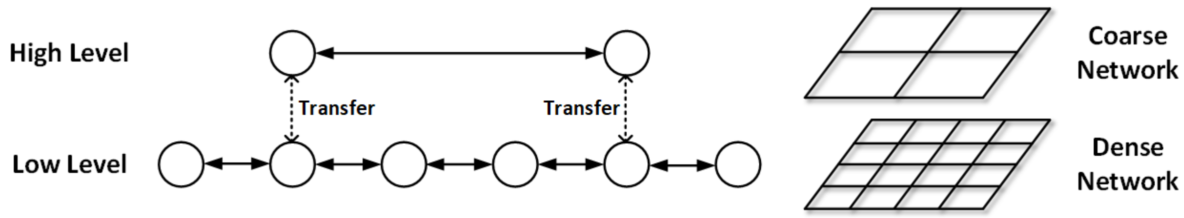


Figure 7 Hierarchy and network densities of multilevel transport

So, using the bicycle as part of the multimodal transport and -network can be beneficial for both traveller and operator of the transit systems. However, a lot is still unknown and based on speculating. Several studies already examined the travel distance willingness of travellers when using the bicycle (See Sub-chapter 2.1) for trips in general and access- and egress trips. Also the trip preferences of travellers are often studied. However, it is yet not known what the impact is of using bicycle as access/egress mode on the travel time, modal split, and travel cost at a large scale. It is also not known how the multimodal network should be organized and designed when using bicycle as access and egress mode. Therefore, this thesis is done to gain more knowledge about using the bicycle as access/egress mode in a multimodal network

1.1 Research Goals & Questions

This thesis will focus on designing a multimodal network with the bicycle as core and study its effects. Core means that the whole multimodal network system is organised and designed around the bicycle as transport mode. Based on the bicycle infrastructure and -behaviour, the other mode networks will be organised. This approach is comparable to a bottom-up approach. First the low-level bicycle network will be organised (Bottom), which will be the base for the high-level transit network and transfer stations (Up). The hypothesis is that this approach will reduce the total travel time for the traveller, increase the use of the bicycle & transit, and decrease the operational & investment cost of transit systems.

1.1.1 Goals

The main goal of this study is: *to design and study the effects of a multimodal network with the bicycle as core on the attractiveness of multimodal passenger transport in terms of travel time, transit-use and operational costs*. In this system, it is preferred that travellers will use the bicycle in at least one leg of the trip. If the destination is nearby, the traveller will do a bicycle only trip. Otherwise, the trip is a multimodal trip with the bicycle as access and/or egress leg. The main leg is one or more transit modes. Furthermore, the P+R stations are taken into account where car users can transfer to a shared-bike.
To support the main goal, several sub-goals were formulated. These sub-goals are based on factors assumed to be important to reach the main goal. A condition to reach these sub-goals is the limitation of higher operational costs.

Sub-goals

- Optimize the use and routes of the bicycle
- Improve bicycle-transit combination use
- Decrease car-use

1.1.2 Research Questions

The main research question was formulated as follows: *To what extent does a multimodal passenger transport network with the bicycle as core reduce the total travel time for travellers and increase the modal split for (multimodal) transit trips, without high investment- and operational cost.*
To answer the main research question, several sub-questions were formulated.

sub-questions

1. How far/long are travellers willing to travel on a bicycle for access and egress trips
    1.1. Which factors influence the travel distance willingness
    1.2. Is the travel distance willingness for access and egress trips different compared to door-to-door trips
2. What are the trip preferences of travellers in a multimodal trip
    2.1. How to incorporate the preferences of the traveller
3. Which multimodal networks and (multilevel) transit services are possible to apply
4. What are the effects of the combined bicycle catchment radius and transit services on the travel time and accessibility
5. Which applications of multimodal networks with the bicycle as core are suitable to implement in a network.
6. To what extent is it possible to decrease car-use by applying a multimodal network with the bicycle as core.

1.2 METHODOLOGY

This thesis will focus on the design of a multimodal network with the bicycle as core and its effects on the travel time, modal split and costs. Based on the sub-questions, a methodology is created. In Figure 8, this methodology is shown. The general structure of this study is: *Literature Study => Theoretical Application => Case study => Conclusion.* Each section in the methodology consists of a specific sub-question, input and output. In the next paragraphs, a more detailed description is given.

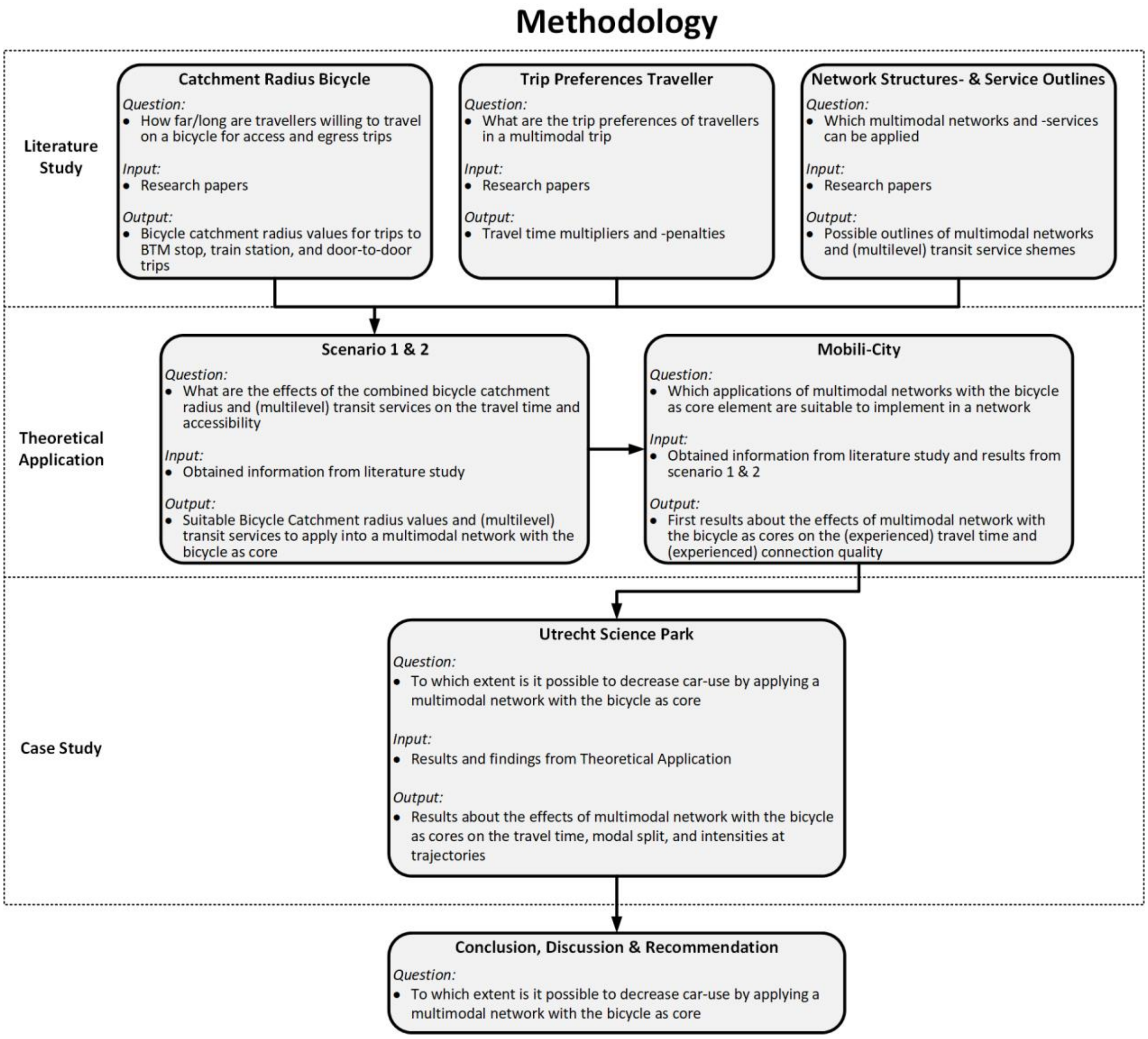


Figure 8 Methodology

Literature Study

The literature study is used to answer the first three sub-questions. first section focuses on obtaining information about the travel distance willingness of cyclists and its factors. Possible factors are the type of bicycle (regular, e-bike, et cetera) and transit system (Bus, train, etc.). The results of this part are needed to determine the catchment radius of the bicycle(s) under different circumstances. This forms the base of this thesis and the design strategy. After completing this section, it should be possible to answer the sub-question "*How far/long are travellers willing to travel on a bicycle for access and egress trips*"

The second section is about the preferences of travellers during a trip. While 1 minute is always 1 minute, travellers may experience this 1 minute it differently. To incorporate the preference, experienced travel time can be used. Factors influencing the experienced travel time are travel mode preference and waiting time for example. To create the experienced travel time, multipliers are used. Each

multiplier represents a preference of the traveller. In this section of the literature study, the preferences of the travellers and the corresponding multipliers are studied. With the results of this section, the experienced travel time can be calculated to determine quality of a route or transport network from a traveller's perspective. With the information from this section, the sub-questions "*What are the effects of the combined bicycle catchment radius and transit services on the travel time and accessibility*" and " can be answered.
The "Multimodal network & -service outlines" section discussed several aspects of a general multimodal network and its services. Subjects are density and hierarchy of a network, and multi-level transit services. After completing this section, the sub-question *"Which multimodal networks and -services are possible"* can be answered.

Theoretical Application
The literature study will give a lot of information about bicycle travel distance willingness, traveller trips preferences and multimodal network & -service outlines. But some information is still missing. First the most suitable bicycle catchment radius needs to be determined. Furthermore, it is still unknown how to combine this information into possible applications of bicycle-based multimodal networks. To find and test these applications, experiments with a high "playability" are needed. Therefore, the theoretical application consists of several simple experiments. These experiments are divided into several (theoretical) scenarios. The first scenarios are simple, with the focus to solve the remaining knowledge gaps. The last scenario is a more complex theoretical area, where the design strategy will be applied. Based on the findings from the literature study and results from the previous scenarios, several alternatives for this area are made. In the chapter Theoretical Application, a detailed description of the experiments is given.
Based on the results of the experiments, the fourth sub-question "*Which outlines of multimodal networks with the bicycle as core are suitable to implement in a transport network*" and *"Which applications of multimodal networks with the bicycle as core are suitable to implement in a network"* can be answered.

Case Study
After the theoretical application, several puzzles of multimodal networks with the bicycle as core will be made. While applications of bicycle-based multimodal networks are tested in the theoretical application, a test in a more complex case with more indicators is needed. Therefore, the case study "Utrecht Science Park" (USP) will be done. The case study will also be used to see if the multimodal network with the bicycle as core can be applied as solution for several mobility issues in the area.

During the case study, the model called Vervoer Regio Utrecht (VRU) is used. This is a static macroscopic model running on the software called Omnitrans. With this model trips of travellers between OD's can be simulated. By making changes in the network, its effects on the travel patterns can be observed. The results of the simulations are helpful to determine whether the bicycle-based multimodal networks still have potential. Furthermore, the results give an indication whether the (sub-)goals will be reached successfully.

Conclusion, discussion & recommendation
After completing the case study, more information about designing a multimodal network with the bicycle as core is obtained. Based on these information and results, a main conclusion can be made about if/which applications of multimodal networks with the bicycle as core have the potential to be applied in practise and are capable of meeting the main- and sub-goals of this study. Furthermore, the overall results of this thesis and the implications of applying it in real life are discussed. Eventually, recommendations are made about when and how a multimodal network with the bicycle as core should be applied.

2 LITERATURE STUDY

As stated, the literature study is divided into “Catchment radius cyclists”, “Trip preferences travellers”, and “Multimodal network & -service outlines”. After the literature study, it should be possible to answer the following sub-questions:

1. How far/long are travellers willing to travel on a bicycle for access and egress trips
   1.1. Which factors influence the travel distance willingness
   1.2. Is it different compared to door-to-door trips
2. What are the trip preferences of travellers in a multimodal trip
   2.1. How to incorporate the preferences of the traveller
3. Which multimodal networks and (multilevel) transit services are possible to apply

In each of the following sub-chapters, information is obtained to answer one of these sub-questions. Furthermore, the obtained information will be used as input in the next chapters.

2.1 CATCHMENT RADIUS CYCLISTS

In this sub-chapter, the main goal is to answer the following sub-question:

“*How far/long are travellers willing to travel on a bicycle for access and egress trips*”
- Which factors influence the travel distance willingness
- Is the travel distance willingness for access and egress trips different compared to door-to-door trips

An important part of this thesis is the maximum distance travellers are willing to travel on a bicycle, called catchment radius. Based on the radius value, the catchment area of a BTM stop, train station or P+R can be determined. As the bicycle types may influence the radius value, different bicycle types are first discussed. After the bicycle type discussion, a literature study about bicycle trips is made. Based on the obtained information, suitable catchment radius values for BTM stops, train stations, P+R and door-to-door trips are determined.

2.1.1 Bicycle types

The bicycles used in the Netherlands to travel from A to B can be roughly divided into regular bicycles (fully human power) and electric-assistance bicycles. While the regular bicycle is still more often used, electric-assistance bicycles are increasingly popular in use (KiM, 2017). Besides these private-owned bicycles, the shared-bike is available. In the next sub-sections, these bicycle types are further discussed.

Regular bicycles

There are many different human powered bicycles from city bicycles to racing- and folding bicycles. The most commonly used bicycle in the Netherlands is the city bicycle, mostly used for full trips and access trips to a stop/station. For access and egress trips, the folding bicycle is also frequently used. Other bicycle types are not commonly used for non-recreational bicycle trips. Therefore, these bicycles are excluded in the rest of this thesis.

Electric-assistance bicycles

Today, there are two types of electric-assistance bicycles available: The E-bike and the Speed Pedelac. Both bicycles have an electrical engine to give pedal-assistance to the user. The cyclist still has to pedal while cycling. In Table 3, several differences between the two types of electric-assistance bikes are formulated. While the e-bike gives only pedal-assistance up to 25 km/h, the speed pedelac can give up to 45 km/h. Due to the 45 km/h limit, the Dutch government sees the speed pedelac as a moped and

is therefore excluded from this thesis. Therefore, speed pedelac users have to obliged to moped legislation. As the law sees this bike as a moped, it is excluded from this thesis.
It should be noted that legislation around e-bike and speed pedalac differ per country. Therefore, the information in Table 3 is only valid for the Netherlands. Furthermore, these regulations may change in the next years.

Table 3 differences e-bike and speed pedelac in the Netherlands (ANWB, 2019)

	e-bike	*Speed pedelac*
Maximal assistance speed	25 km/h	45[i] km/h
Maximum power	250 W	4.000 W
License required	No	Yes: AM
Helm compulsory	No	Yes
WA-insurance required	No	Yes
License plate required	No	Yes: Yellow

Shared-bike
In the Netherlands, shared-bikes are increasingly available for travellers. With a shared-bike, travellers can rent a bike for a certain time period or trip. The exact apply method differs per company and region. The study of Van Waes et al., (2018) identified four categories as shown in Figure 9. Firstly, the systems can be divided into station-based and station-less/free-floating. With station-based, shared-bikes can only return (ending the rent) at certain stations. The free-floating bikes can be dropped-off at any (legal) location or drop zones. For several systems, the bike has to be returned to the start location (A-A trips/tour) while other systems allow one-way trips (A-to-B trips).

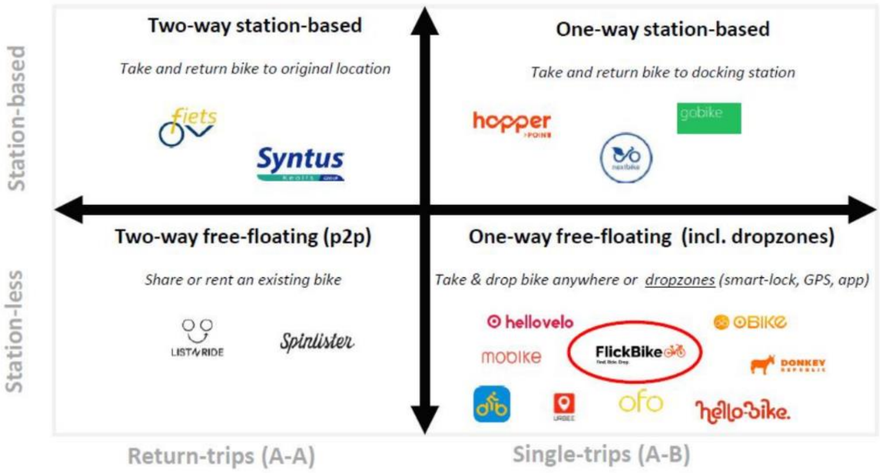


Figure 9 Categories shared-bikes (Van Waes, Farla, Frenken, De Jong, & Raven, 2018)

Currently, the wide-scale applied shared-bike systems only use modified regular bicycle types. There are shared E-bike systems however, only on a smaller scale and mostly according to a two-way station-based system. Likely reasons for the low appliance of share-e-bikes are the high investment cost (compared to non-electrical) and higher risk of battery- and bicycle theft.
For the sake of simplicity, it is assumed in this thesis that the differences between the shared-bike system have, almost, no impact on the results.

2.1.2 Bike trips

As there are different bike types and also differences between private-owned bikes and shared-bikes, travellers will use these bikes differently. In this sub-chapter, the bike trips are studied. The main focus is on travel distance, travel time and average travel speed. This sub-chapter is divided into different sections. First, the bike trips made in general are studied. In this part, no distinction in trip types and

[i] The cyclist has to obliged to the maximum allowed speed on the road-section

Origin-Destination (OD) are made. The next part is about the access and egress trips done by private-owned bikes. In the last part, the shared-bike trips are discussed.

Bike trips in general

In the report Mobiliteitsbeeld 2017 of the Dutch Institute for Transport Policy Analysis (Kennisinstituut voor Mobiliteitsbeeld (KiM)), differences between the travel use of regular bike and e-bike were studied. Table 4 shows the average cycle distance per bike type for different age groups. Overall, travellers using an e-bike have a higher average travel distance. For almost all age groups, this difference is mainly caused by a longer travel time. Apparently, e-bike users are not only faster than regular bike users, but also accept a longer travel time by bicycle. The 35-49 year group, has a smaller average distance for both regular bike and e-bike. It is unknown why these numbers are lower for this group (even lower than 75+ year group).
In Figure 10, the modal share values of the regular bike and e-bike per distance class are shown. For the regular bicycle, the highest peak is at a distance class of 1,0-2,5 km with a value of 40 %. With modal share values fluctuating around 5 %, the e-bike is much more constant over distance. For low cycle distances, the regular bike is more popular than the e-bike. However, for distances above the 7.5 km, the e-bike has a higher modal share.
The average speed of the regular- and e-bike per age group, is shown in Figure 11. On average, the travel speed for e-bike is 12,8 km/h and for regular 12,3 km/h. It should be noted that these speed values are an average for the full cycle distance and include waiting for a red light et cetera. The results show that the speed difference between the bikes is quite small. Only for the youngest age group, the difference is larger than 1 km/h. Apparently, e-bike users do not tend to travel much faster than regular bicycle users.
The discussed results show that e-bike users are willing to travel further and longer, than regular bike users. While the e-bike gives pedal assistance up-to 25 km/h, the average user will not cycle much faster than regular bike users. So, the higher average cycle distances made by e-bike users is mostly influenced by longer travel times. A possible explanation for the relatively small speed difference are obstacles like traffic lights and busy city streets. These circumstances will make it more difficult for E-bike users to ride faster than a regular cyclist. The results also indicate, that the difference between the age groups is relatively small. Therefore, it is not necessary to make a distinction in the age of the bicycle users.

Table 4 average trip distance e-bike and regular bike per age group (KiM, 2017)

	Average distance e-bike (km)	*Average distance regular bike (km)*	*Difference travel distance (km)*	*Difference caused by longer travel time (%)*	*Difference caused by faster travel speed (%)*
12-34 year	5,1	3,7	1,5	30	70
35-49 year	4,4	3,1	1,3	60	40
50-65 year	5,0	3,8	1,2	70	30
65-74 year	5,7	3,8	1,9	80	20
75+ year	5,4	3,2	2,2	90	10
All	5,2	3,6	1,6	85	15

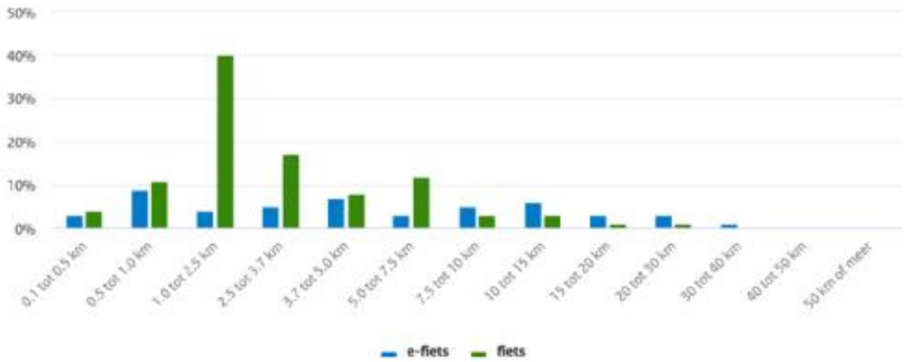


Figure 10 modal share e-bike and regular bike per distance class in the Netherlands (KiM, 2017)

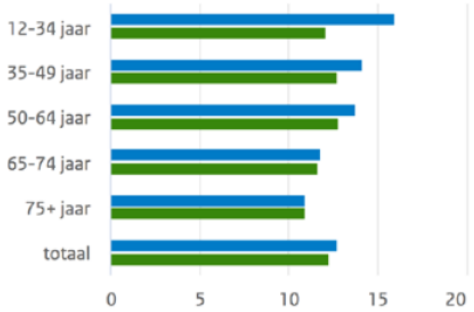


Figure 11 average speed regular bike and e-bike per age group (KiM, 2017)

Access and egress bicycle trips

In the previous part, general bicycle trips were discussed without making distinction between bike-only trips and multimodal use. In this part, access and egress bicycle trips are discussed.

The study of Krygsman et al. (2004) (Figure 12) shows that on the access side, the travel time distribution of walking and cycling are comparable. The 50 % percentile is around 8 minutes, which is at a travel speed of 12,3 km/h around 1,6 km. With a median travel time of 11 minutes (2,3 km), the egress trip time is much longer. Compared to the results of the KiM report, the travel distances for both access and egress are much smaller in this study. Apparently, cyclists from and to a train station have a lower catchment radius than the average bicycle user for bicycle-only trips. Between access and egress, the egress trips are generally longer. However, the 5 % values are almost the same (around 20 minutes). So, as the travel time increases, the difference between access and egress becomes smaller. Apparently, if the cycling travel time is less than 5 minutes, travellers prefer to walk.

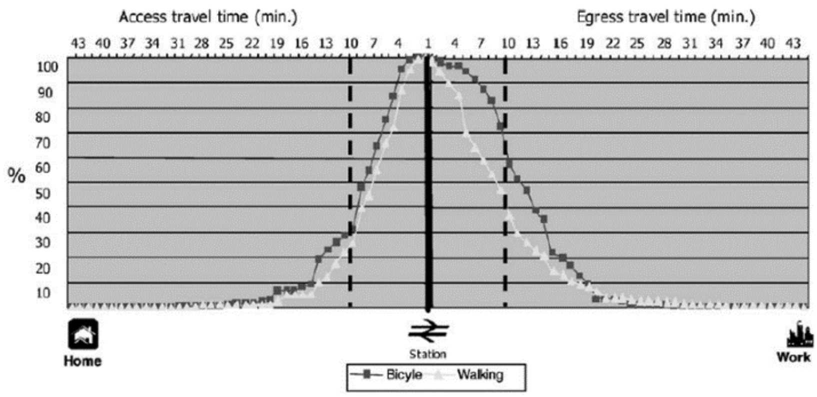


Figure 12 cumulative frequency distribution access and egress from/to train station (Krygsman, Dijst, & Arentze, 2004)

In the study done by Rijsman (2018), the travel distance willingness of cyclists for access trips to tram stops in Den Haag is determined as shown in Figure 13. According to this figure, the 25th percentile is around 700 m, 50th around 1000 m, and the 75th around 1500 m. Also in this study, the travel distances covered by bicycle is less than the travel distance reported by KiM for bicycle-only trips. Furthermore, the values are lower than the access side values from the previously described study. A possible explanation is the higher attraction of train stations compared to tram stops. Also the high network density of the Den Haag tram network may affect the results, as most bike users do not have to travel far for a tram stop.

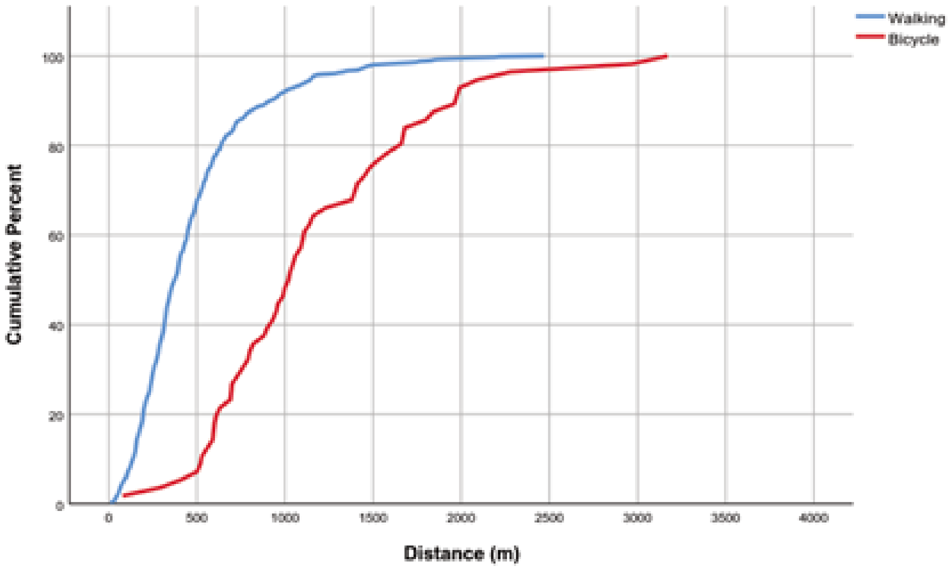


Figure 13 cumulative distribution access to bus (Rijsman, 2018)

In Figure 14, results from the study done by Shelat et al. (2018) are shown. This figure shows the modal share of access and egress trips to train and BTM per distance. For access trips, the modal share of cycling becomes higher if the distance increases. For trips to a train station, the bicycle has the highest modal share around 2,5 km and for trips to a BTM station 3 km. Due to the low number of respondents and rounding-off of the stated trip distance, the BTM curve is more fluctuating. For egress trips, the bicycle is less popular. A likely explanation is the absence or limited availability of the bicycle as mode option. Like for access trips to a train station, the bicycle has for the egress trips the highest modal share around 2,5 km. For egress trips from BTM stations, the highest modal share value is around 4 km, which is further than for access trips to a BTM station.

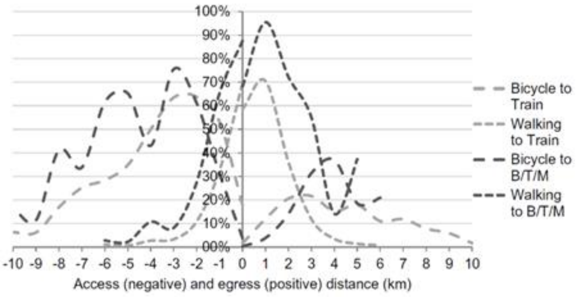


Figure 14 Modal share per distance class access and egress (Shelat, Huisman, & van Oort, 2018)

In a study done by Brand et al. (2017) the bicycle access trips to two different bus operators were studied. The first one is called Comfortnet, which function as a regular bus service. The other is R-Net which is more of a Dutch Bus Rapid Transit (BRT) service, with a higher operational speed and frequency than Comfortnet. The trip distances were obtained by doing surveys. The results are shown in Figure 15. According to the results, travellers cycle much further for the R-Net busses than for Comfortnet. At a percentile of 50 %, the distance is for Comfortnet approximately 650 m and for R-net 1100 m. Apparently, travellers are willing to cycle further for a higher quality bus service (in terms of speed and frequency).

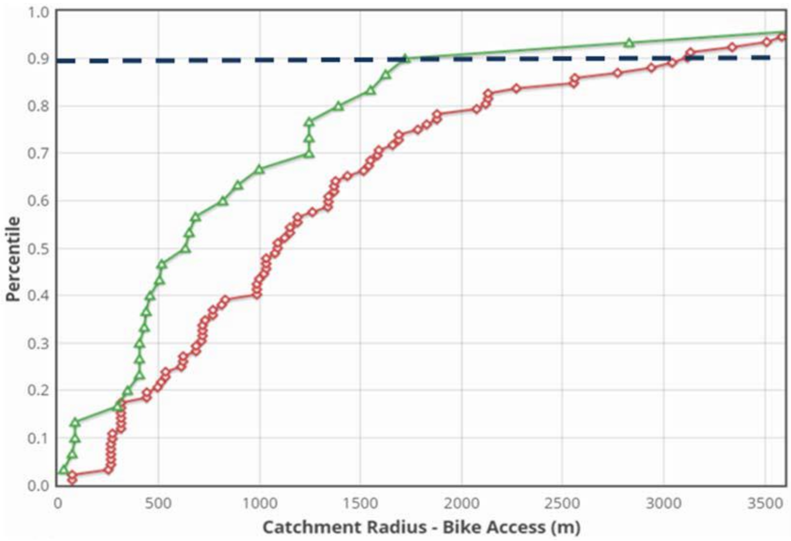


Figure 15 bicycle access trip distance to Comfortnet (green) and R-Net (Red) (Brand, Hoogendoorn, van Oort, & Schalkwijk, 2017)

Shared-bike trips

In a study done by Caulfield, et al., (2017), data from the shared-bike system in Cork, Ireland, was analysed. In Figure 16, a distribution of travel times is shown and in Table 5 the number of trips for each travel time and distance group. The 50th percentile is, approximately, a bit higher than 6 minutes. The same table show that the cycling distance was lower than 1288 m for 47,4 % of the trips. Approximately, the 50th percentile is around the 1300 m. Using both percentile values gives an average speed of around 12,5 km/h, which is comparable with the average speed value from the previous study. As each time group has almost the same share as its distance group equivalent, the travel time and distance values can be used to calculate approximate average speed values. The results of combining them are shown in Table 6. This table shows that the all groups have more or less the same average speed. Therefore, it can be assumed that the travel time differences are mostly influenced by the travel distance. Furthermore, the average travel speed from the previous study for the regular bike is also applicable for foreign cities and shared-bikes.

Compared to the results of the studies on the regular bicycle users, shared-bike users have a shorter cycling distance. A possible cause is the, likely, more limited number of very long bicycle trips (>10 km) for shared-bike trips compared to regular bike trips. Still, the results of this study indicate that shared-bike users cover shorter travel distances than regular bike users.

Table 5 amount of observations for eacht travel time and distance group (Caulfield, O'Mahony, Brazil, & Weldon, 2017)

	N	*%*
Less than 4 min.	58.417	22,3
4 to 6 min.	65.300	25,0
6 to 9 min.	68.494	26,2
More than 9 min.	69.167	26,5
Less than 852 m	59.456	22,7
852-1288 m	64.653	24,7
1289-1848 m	67.366	25,8
More than 1849 m	70.003	26,8

Table 6 Average speed per distance class (Caulfield, O'Mahony, Brazil, & Weldon, 2017)

	Approximate average speed (km/h)
Less than 4 min / 852 m	12,8
4 to 6 min. / 852 to 1288 m	12,9
6 to 9 min. / 1289 to 1848 m	12,3
More than 9 min. / 1849 m	12,3

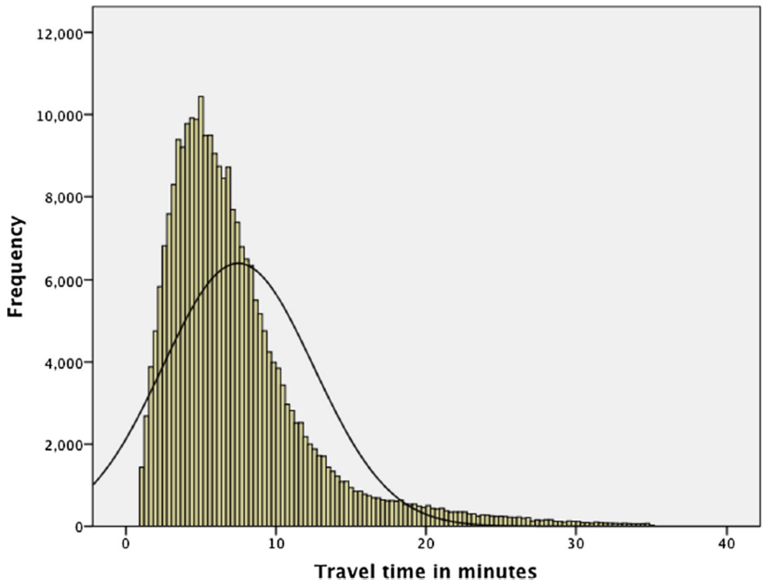


Figure 16 Travel time distribution (Caulfield, O'Mahony, Brazil, & Weldon, 2017)

The study done by Ma et al. (2019), analysed bicycle trips in Nanjing, China done by docked- or free-floating shared-bikes (two different companies). Table 7 Indicate large differences in the use of both shared-bike systems. As Figure 17 shows, these patterns are mainly caused by the significant amount of +3 km trips for docked bikes. It is likely that the difference is, for a large part, influenced by the different prize scheme. If the trips are shorter than 30 minutes, many travellers are willing to pay for a free-floating share-biked. For longer trips they find it too expensive and choose for a docked shared-bike.

While the trip distance and -time were different, the average speeds was similar. For free-floating, it was 6,0 km/h and for docked 5,6 km/h. Compared to the average speed calculated in the studies of Caulfield et al. (2017) and KiM (2017), these speed values were more than 50 % lower. Possible causes are the high traffic intensities on the road and/or cycling cultural differences between Europe and China. The trip times are more similar. In the study of Caulfield et al. (2017), the median trip time was around 6 minutes which is 1,5 minutes lower than the free-floating shared-bikes. While the speed differences are large, both studies do not differ much in preferred trip times.

Table 7 Results free-floating and docked shared-bikes (Ma et al., 2019)

	Free-floating	*Docked*
Sample size	2.058.819	890.369
Cost	1 Yuan/0,15 $ per 30 min.	First 2 hours free
Average trip distance	1035 m	1488 m
Average trip time	10,4 min.	15,9 min.
Average trip speed	6.0 km/h	5.6 km/h
50th percentile travel distance	~750 m	~1100 m
50th percentile travel time	~7,5 min.	~10 min.

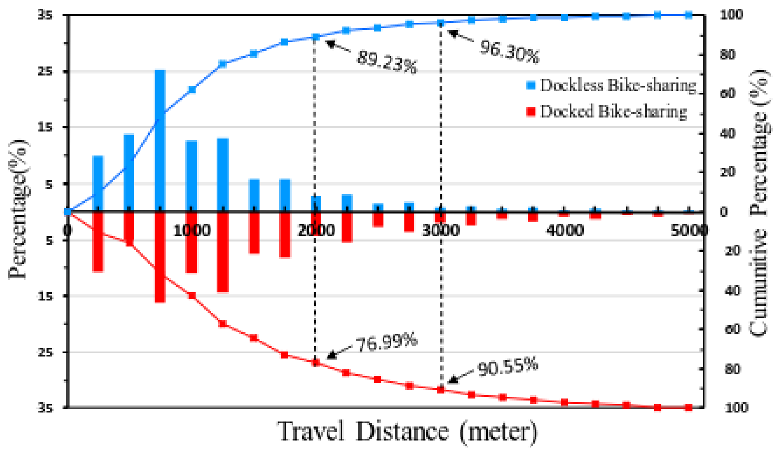


Figure 17 Cumulative curves travel distance shared-bike use (Ma et al., 2019)

2.1.3 Catchment radius cyclists

Based on the obtained information in this sub-chapter, catchment radius values for cyclists are determined. The discussed studies showed that the observed cycling distance were different per bicycle type (regular, E-bike and shared-bike). Therefore, a distinction should be made between bicycle types when determine the catchment radius. The studies also indicate difference between door-to-door, access, and egress bicycle trips. Furthermore, the access and egress trip distance were different for BTM stop and train station. For bicycle egress trips from P+R's, no (reliable) sources or studies were found. So, multiple catchment radius values for cyclists need to be determined.

While the obtained information in the literature study are useful, there are several issues. The first issue is that all studies were using observed cycling trips, the so called "chosen" travellers. Downside of this method is that it excludes the travellers using different modes for their trips, the so called "non-chosen" travellers. They might not have chosen for the bicycle as mode, due to a too high cycling distance. Therefore, using catchment radius values for cyclists purely based on observed cycling trips can be too much biased. Another issue are the observed travel trips for travelling from or to a BTM stop. Especially within a city, the BTM network is often dense. Therefore, travellers do not have to travel far for a BTM. So, it is possible that the traveller is willing to cycle much further for a BTM stop than observed. To a lesser extent, this also account for cycling trips to a train station. The last issue is the limited available information of E-bike trips, especially about access and egress trips. It is likely that the E-bike is currently mostly used for door-to-door trips. Furthermore, it can be assumed that the number of travellers using a private-owned E-bike for only egress trips is almost zero, due to the price of an E-bike and the risk of theft.

While it is possible to estimate catchment radius values for cyclists, it will be far from accurate. Therefore, these values should be more seen as a first indication, and not as a fact or hard limit. The determined catchment radius values are shown in

Table 10. Firstly, it is assumed that the regular bicycle and E-bike are used for door-to-door, and access trips, while the shared-bike is used for egress trips. The values for door-to-door trips are based on the average trip distance of both regular bicycle and E-bike in the KiM report.
For determine the access trip distance to a BTM stop and train stations on a regular bicycle, multiple studies can be used. To make an overview of the results, Table 8 is made. According to the percentile values, cyclists are travelling a longer distance for a train station than a BTM stop. Therefore, it can be concluded that the cycling catchment area of a train station is larger than a BTM stop. While the 50th percentile for access trips to a train station is 1600 m, the highest modal share is at 2500 m. It may indicate that travellers are willing to travel much further to a train station than needed. Eventually, it is chosen to use 2500 m as cycling distance willingness value for bicycle trips to a train station.
Determine the catchment radius of the BTM for regular bicycles is more complicated. While the tram and BRT have comparable results, the regular bus has much lower distance values. Meanwhile, the study of Shelat et al. (2018) indicate the highest modal share for bicycle access trips to BTM at 3000 m. Firstly, the comparable results of the tram and BRT indicate that it is possible to use the same catchment radius values for bus, tram and metro, as long as the quality for the bus service is not too low. As the study of Brand et al. (2017) indicate, the quality of the BTM service is an important factor in the catchment radius of the bicycle. Furthermore, it is possible that the travellers were willing to travel further than necessary. This could explain the differences between the study of Shelat and the other studies. Eventually, it is chosen to use a value range for the catchment radius of the BTM. the lowest value (1000 m) is based on the 50th percentile value of the tram and BRT. The highest value (2000 m) is used when the quality of the BTM service is comparable to a train service.
Based on the difference in door-to-door trip distance between regular- and E-bike, the access trip distance with the E-bike can be determined. For door-to-door trips, the distance on an E-bike is approximately 40 % higher. Using this value for access trips creates a catchment radius of 3600 m for trips to a train station and a value range of 1400-2900 m for trips to a BTM stop.
In Table 9, the results of the discussed shared-bike studies are summarized. Based on these results, the catchment radius of BTM stops and P+R for egress shared-bike trips is set on 1500 m. As travellers are willing to travel further to train station, the egress trip distance for shared-bike trips from train stations is set at 2000 m.

Table 8 access trip distance per mode

	Bus regular (Brand et al., 2017))	*BRT (Brand et al., (2017))*	*Tram (Rijsman, 2018)*	*Train access (Krygsman et al., (2004))*
25th percentile	~400 m	~600 m	700 m	5 min / 1000 m
50th percentile	~650 m	~1100 m	1000 m	8 min / 1600 m
75th percentile	~1250 m	~1800 m	1500 m	12 min / 2500 m

Table 9 trip characteristics shared-bikes

	Caulfield et al. (2017)	*Ma et al. (2019)*	*Ma et al. (2018) => 12,5 km/h*
Average travel speed	~12,5 km/h	6,0 km/h	12,5 km/h
Average trip distance	9 min. (~1,9 km)	1035 m	2.153 m
25th percentile	~900 m	~500 m	~1000 m
50th percentile	~1300 m	~750 m	~1600 m
75th percentile	~1900 m	~1500 m	~3100 m

Table 10 Final cycling distance willingness values.

	BTM		*Train*		*P+R*	*Door-to-Door*
	Access	Egress	Access	Egress	Egress	
Regular bicycle	1000-2000 m	-	2500 m	-	-	3500 m
E-bike	1400-2900 m	-	3600 m	-	-	5000 m
Shared-bike	-	1500 m	-	2000 m	1500 m	-

2.1.4 Conclusion

The first sub-question was:
how far/long are travellers willing to use a bicycle for access and egress trips?
Firstly, it appeared that the bicycle type has a significant influence on the cycling distance willingness on access, egress and door-to-door bicycle trips. With the E-bike, these trips can be up to 40 % longer compared to trips on a regular bicycle. However, cyclists on a E-bike are only a bit faster than regular bicycle users. The literature study also indicated that travellers are willing to cycle much further for door-to-door bicycle trips than for access- and egress trips. Table 10 the answer to the first sub-question. For access trips to a BTM stop it appeared to be difficult to determine a suitable catchment radius, as it depends greatly on the frequency and operational speed of the BTM service.

2.2 Trip preferences travellers

The sub-question central in this sub-chapter is:

"What are the trip preferences of travellers in a multimodal trip"

- How to incorporate the preferences of the traveller into the travel time calculations

The preferences and choices of the traveller can be seen as the most important part of any (multimodal) trip. No matter how a route, trip or network is organized, it will be a failure if it does not fulfil the traveller's preferences. Therefore, it is important to know these travel preferences, both general and multimodal specific.
In a study done by Hoogendoorn-Lanser (2005), travel behaviour in a multimodal network was modelled. One of the results were contributions of trip attribute classes on the total trip utility (with train as main leg), shown in Figure 18. This figure indicates that the utility of, in this case, a main train trip is mostly determined by in-vehicle times, Frequency-related attributes and mode-specific constants. Therefore, the further literature study about the trip preferences of the travellers should focus on these aspects.
For this thesis, it is preferred to convert the preferences of travellers into travel time multipliers and -penalties. This makes it possible to calculate the 'experienced' travel time. The experienced travel time reflects the 'subjective' trip time and attractiveness of a trip from the perspective of the traveller. Therefore, only studies determining multipliers and/or penalties are used.

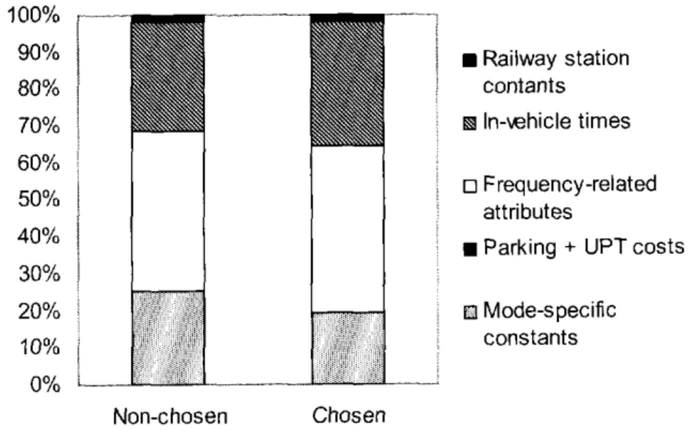


Figure 18 contributions of trip attribute classes[II] (Hoogendoorn-Lanser, 2005)

2.2.1 Travel time multipliers

The travel time consisted of several parts like walking time, in-vehicle time, and waiting time. While 1-minute is always 1-minute, travellers may experience it differently in each part. For example, one minute waiting on a platform for the train feels slower than one minute sitting in a driving train. About experienced travel time, several studies were done with different results. In the next part, four studies focusing on travel time multipliers are discussed. These studies are: Bovy & Hoogendoorn-Lanser (2005), Arentze & Molin (2013), Wardman (2014), and Wardman, et al., (2016).

In the study of Bovy, et al., (2005)[III] travel time multipliers were calculated, based on travel behaviour of travellers using a certain train corridor in the Netherlands as main leg. These multipliers, shown in Table 11, are relative to the train in-vehicle time (IVT). The private modes consist of bikes and cars (both driver and passenger), and the transit of bus, tram and metro. Furthermore, the transfers multipliers are for both within and between modes. According to the results, travellers experience waiting (both first and at transfer) more than twice as long, than train IVT. Also walking during transferring has a multiplier close to two. An interesting result is the access-transit multiplier. Apparently, travellers experience the IVT in the BTM faster than in the train. Furthermore, the access with private mode is twice as high as access BTM. However, there is one side note with the transit results. To make use of PT as access mode, travellers have to walk and wait at a PT stop. Including these factors will most likely increase the multiplier of the transit and comparable with the private modes.

Table 11 Multipliers trip with train as main leg (Bovy & Hoogendoorn-Lanser, 2005)

	Multiplier
Access IVT – Private modes	1.6
Access IVT - transit	0.8
Train IVT	1.0
First wait time	2.2
Waiting time at transfers	2.2
Walking time at transfers	1.9

The study of Arentze, et al., (2013), determined several multipliers by doing a survey. One of the results were walk and wait time multipliers with different train travel distances as main mode, shown in Table 12. The results show that if the train distance increase, the multiplier values also increase. Interesting results are the wait time multipliers, which are much lower compared to the wait time values in the previous study. The cause of this difference is unknown. The determined multipliers for walk time are close to the walk time during transferring from the previous study.

[II] In this figure the results at the "chosen" group are contributions for trips chosen by the traveler and the "non-chosen" other available trips
[III] This study is related with the study of Hoogendoorn-Lanser (2005)

Table 12 Multipliers trip with different train travel distances (Arentze & Molin, 2013)

	20 km	*65 km*
Walk time	1.85	2.25
Wait time	1.23	1.50

A detailed meta-analysis study about Out-of-Vehicle-Time (OVT) multipliers done by Wardman (2014), the walk time, access time, wait time, and transfer time multipliers (European average) for different scenario's (journey purpose and per mode) were calculated. These calculated multipliers are relative to the IVT. In Table 13, these results are shown. On average, the multiplier values are between the 1.5 and 2.0. So, the experienced travel time will be much higher than the factual. Furthermore, the multipliers indicate that the travellers experience one minute waiting longer than one minute walking. However, the difference is not large (less than 10 %). Another interesting result is the large waiting time multiplier difference between bus and rail. Apparently, travellers experience waiting for the bus longer than waiting for the train. Also the access time has large multiplier difference for bus and rail. But this study has combined all access modes for determine the access time multiplier.
So, the access time differences can be caused by the use of different access modes. While the access to the bus is mostly walking, the bike and bus are more often the access modes to a train station (van Nes, Hansen, & Winnips, 2014). Therefore, these two multipliers are not useable as they are dependable on the access mode choice. Compared to the previous studies, the results of this study are similar. Only the waiting time is in some occasions significantly lower than the first study, but still much higher than the second study. However, the multipliers in this study are relative to the general IVT, but the other studies relative to IVT of the train. It is unknown if this creates significant differences in the multiplier differences.

Table 13 OVT Multipliers by Journey Purpose and by mode (Wardman, 2014)

	All	*Commute*	*Leisure*	*Business*	*Other*	*Bus*	*Rail*
Walk time	1.68	1.69	1.70	1.52	1.65	1.64	1.65
Access time	1.68	1.68	1.82	1.66	1.55	1.62	1.29
Wait time	1.80	1.83	1.76	1.54	1.84	1.74	1.49
Transfer wait	1.84	1.59	1.99	1.28	2.12	1.92	1.83

The study of Yap, et al., (2018), smart card data (revealed preference) from the region of Den Haag was used to determine the multipliers for wait time, transfer time, and tram IVT, relative to the IVT of the bus. Furthermore, it made a distinction between frequent and infrequent travellers. The results are shown in Table 14. The table show that the multiplier for both wait- and transfer time was 1.5 for all travellers (frequent and infrequent). Furthermore, the tram IVT is determined as only 60 % of the bus IVT. Apparently, travellers prefer the tram much more than the bus. Compared to the bus multipliers of Wardman (2014), the multiplier values are a bit lower. Likely causes are the difference between stated and revealed preference studies, and difference between case study specific versus meta-study.

Table 14 multipliers per frequency use (Yap, Cats, & van Arem, 2018)

	Average	*Frequent*	*Infrequent*
In-vehicle time tram	0.6	0.6	0.6
In-vehicle time bus	1.0	1.0	1.0
Waiting- & transfer time	1.6	1.5	1.5

In the study of Van Mil, et al., (2018) factors influencing the bicycle-transit mode combination and determine the interrelations. According to this study, one minute of bicycle time is equal to 1,36 minutes of train time. Apparently, travellers have a higher preference for using the bicycle than using the train.

2.2.2 Transfer penalty

As indicated in the begin of this sub-chapter, frequency related attributes are an important factor in the total trip utility. It consisted the frequency of the PT service line and transfers within and between modes. Generally, a low frequency has several downsides for the user. Assuming travellers arrive random at the station (not valid for very low frequencies), a lower frequency means a longer average waiting time (which the traveller experience slower). Furthermore, the consequences of missing the planned PT vehicle are higher on low frequency service lines (longer time waiting for the next one). In the paragraph Travel time, the waiting time was already discussed. Therefore, additional waiting time during a transfer is excluded in this paragraph. While transfer and frequency/headway are two different factors in the trip, some studies combined transfer and frequency to determine a penalty value.
In the study of Bovy, et al., (2005) transfer penalty values were calculated by making a distinction between high frequency services (8 or more vehicles per hour) and low frequency services (less than 8). According to this study, travellers experience a transfer on a high frequency line as an extra travel time of 5 minutes, and on a low frequency line 11 minutes (added to the waiting time).
Based on smartcard data, the study of Yap, et al., (2018) also calculated a transfer penalty for both frequent and infrequent users of a bus or tram service line. The result was a penalty of 5,2 minutes for both traveller types. Different from other studies, this value is not dependable of frequency, waiting time or crowding. Therefore, this penalty value can be seen as a penalty pure for undertaking a transfer.
The study of Van Mil, et al., (2018) also studied the transfer penalty. It was found that 1 minute of bicycle time is equal to 0,18 transfer between transit modes. So, one transfer is equal to 5,6 minutes of bicycle time. This value is almost equal to the penalty found in the study of Yap, et al., (2018).

2.2.3 Final multiplier- & penalty values

In this sub-chapter results, graphs, tables, with multiplier and penalty values for different factors and aspects are shown and discussed. Based on the obtained information, final multiplier- and penalty values to use in this thesis are determined. However, directly comparing these studies is difficult, as the methods and/or focuses were different. Furthermore, some studies have the in-vehicle time (IVT) of the bus as reference point while others have the IVT of the train. For this thesis, it is also necessary to have a reference point. As several papers use the IVT of the train as reference point, it will also be used in this thesis. Determining an IVT BTM multiplier appeared to be very difficult. In the paper of Bovy, et al., (2005) a multiplier of 0,8 is stated. However, this is when a BTM is used as access mode with the train as main trip mode. For this thesis, a multiplier for IVT BTM as main trip mode is preferred. The study of Yap, et al., (2018) shows a much higher preference for the tram compared to the bus. But, if the bus functions more like a Bus Rapid Transit (BRT), the difference will be probably smaller.
Based on all this information , the IVT multiplier of the BTM is set on 1,2. This reflects a small dispreference of the BTM compared to the train due to a lower operational speed of BTM vehicles compared to train.
For the walking- and waiting time multipliers, more values were found. To create an overview, Table 15 is made. This table shows a large range of different multiplier values. From a practical point of view, it is preferred to use walk- and waiting time multipliers valid for all transit modes. To determine the final multiplier values, the average values are calculated. Based on these values, the walking- and waiting time multipliers are both set at 1,75.
The study of Van Mil, et al., (2018) showed that 1 minute of bicycle time is equal to 1,36 minutes of train time. So, one minute train time is equal to 0,75 minutes on a bicycle. This value will be used in this thesis as multiplier for the cycling time.
Also information about transfer penalties was obtained. The studies of Yap, et al., (2018) and Van Mil, et al., (2018) indicated both a transfer penalty of around 5,5 minutes. The study of Bovy, et al., (2005) indicated a transfer penalty of 5 minutes when the frequency is higher than 8 vehicles per hour, and 11 minutes when lower than 8. As all three studies indicated a transfer penalty of around the 5,5 minutes, the transfer penalty in this thesis is set at 5,5 minutes.

Table 15 comparison of wait- and walk time multipliers from different studies

	Bus		*Train*		
	Wardman, et al., (2014)	Yap, et al., (2018)	Wardman, et al., (2014)	Bovy, et al., (2005)	Arentze, et al., (2013)
Walk time	1.64	1.5	1.65	1.9	1.85-2.25
Wait time	1.74	1.5	1.49	2.2	1.23-1.50

Table 16 multiplier and penalty values

	Value
Walking time	1,75
Waiting time	1,75
Cycling time	0,75
In-vehicle time BTM	1,2
In-vehicle time Train	1
Transfer penalty	5,5 min

2.2.4 Conclusion

The sub-question central in this sub-chapter was: *What are the trip preferences of travellers in a multimodal trip.* The studies indicated a high dispreference for walking to a transit stop or -station and waiting for the transit vehicle at this stop or station. Furthermore, travellers also dislike having transfers between transit modes. These conclusions show that it is important to limit the waiting time at and the number of transfers.

2.3 Multimodal Network & -Service Outlines

In this sub-chapter, the following sub-question is central:

"*Which multimodal networks and (multilevel) transit services are possible to apply*"

In the introduction, a small description of a multimodal passenger transport network was given. It descripted about access/main/egress legs, network density, and -hierarchy. In this chapter, the network design is further discussed. The core of this literature study sub-chapter is the study "Design of multimodal transport networks" done by Van Nes, (2002), with additions of other studies. First, different parts of network design are discussed including design examples.

Network hierarchy and density

In most cases, multimodal transport consists of a network hierarchy with different network densities. The access and/or egress leg trips are at a low-level where the network is dense, the trip distances are short, and the travel speed relatively low. The main leg is at a high network level with a coarse network, long travel distance, and a high travel speed. At transfer stations, the traveller can transfer between a low-level network mode and a high-level mode. Main question is how large the difference between the different network levels should be.
According to the study of Van Nes, (2002), a scale-factor of 3 between two transit networks for both stop- and line spacing should be applied. This factor can also be applied for road spacing (van Nes R. , 2002) and bicycle paths (Bach, 1999). For road travel speed, a scale factor of 1.67 (van Nes R. , 2002) was determined. As the spacing factors of road traffic and transit are the same, it is assumed that the speed scale-factor for transit is also 1.67. For the bicycle, no speed factor will be applied.

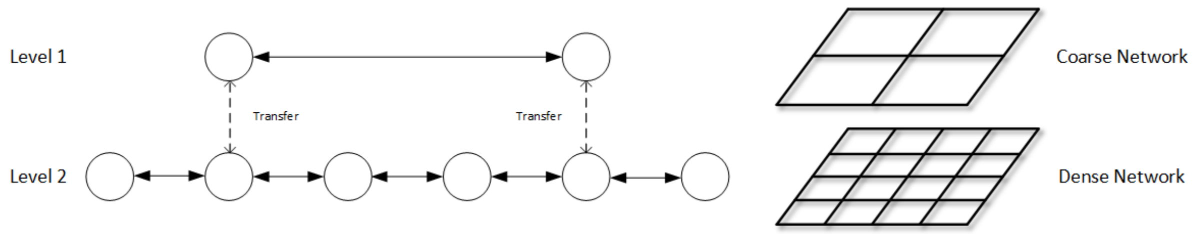


Figure 19 Hierarchy and network densities multimodal transport

Multimodal network service line

When looking at two-level multimodal systems on a specific line, several applications for transit services are possible. Three of these applications are shown in the Figure 20. In these examples, both levels consist of transit service lines. With the express system, a low-level transit service stops at every node/stop and a express transit service only at some of them. The traveller can choose between the slow service with no transfer or the fast service with, in most cases, one or two transfers. In a zone system, the transit line function in a specific area as a low-level transit service. Outside this area, the transit line will behave as a express line with much fewer stops. With the trunk-feeder system, the low-level transit services function as a connector between the nodes and the high level stations. With the high level transit services, travellers can travel to other areas. In the study of Van Nes (2002), these three applications were compared with a single-level transit service in different scenarios. It appeared that the two-level corridors only scored better for long distances (interurban). Exception was the zone system application. With dedicated lanes, it can be already an interesting option for trips longer than 6 kilometres. However, its only effective if the trip is city-centre focused. For other trip destinations, the zone system is less suitable.

When applying the bike as access and egress, it will change the outline of the multi-level services. In Figure 21, the adapted versions including the bike as access or egress are shown. In these examples, the traveller is willing to cycle to the neighbouring node if that node is connected with a transit service. For all approaches, the low level transit service does not have to stop at every node. As the number of stops decreases, the vehicle trip time will also decrease (positive for the traveller). With a lower vehicle trip time, the same vehicle can do more scheduled trips per hour, which saves costs (positive for the operator). This also accounts for the high-level transit services. In the express system approach, both low- and high level have much fewer stops compared to the transit-only version. For short corridors, it will become questionable if a high level transit service is still necessary/useful. Main reason is the balance between saving (in-vehicle) travel time versus an extra transfer (+ extra waiting time).

In the zone system application, fewer transit service lines are needed. Furthermore, each service has fewer stops. As there are fewer service lines, more vehicles to other services can be allocated. Dependable on the circumstances, it seems also applicable for short corridors. Only if the traveller demand is high for multiple nodes, a zone system is not suitable for short trips as it will behave almost the same as a low level transit line.

For the trunk-feeder system, more nodes to a single trunk-feeder can be connected. In total, fewer transfer stations between the low- and high level transit services are needed. Also, fewer separate low level transit services are needed. This makes it possible to allocate more vehicles to a single service line. Like for the express system, applying the trunk-feeder system for short corridors is questionable. Especially, since most travellers have at least one extra transfer. Therefore, the total travel time saving should be significant higher before this approach is attractive for travellers.

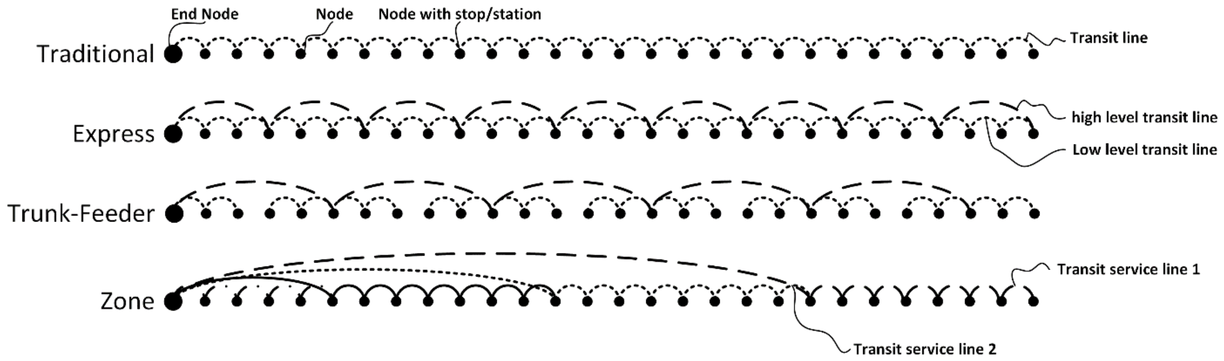


Figure 20 multi-level services without bicycle

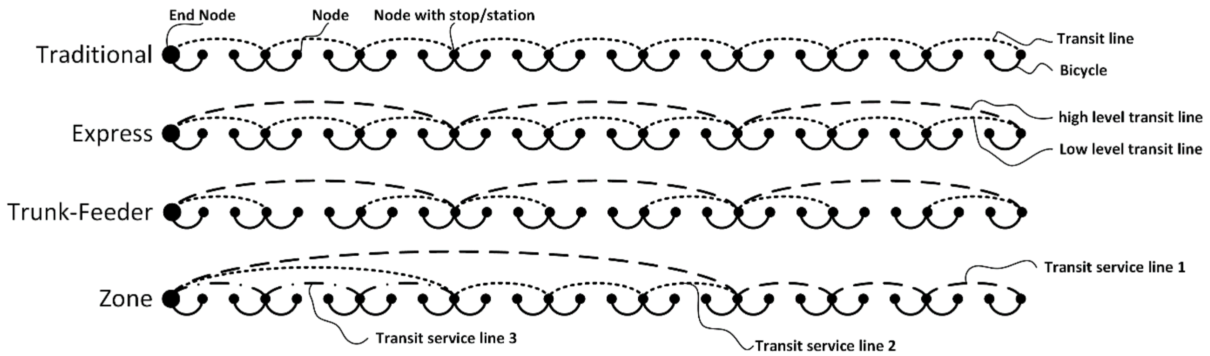


Figure 21 multi-level services including bike

Conclusion

In this sub-chapter, the focus was on following sub-question:
"*Which multimodal networks and (multilevel) transit services are possible to apply*"

For transit systems, different network levels are often applied. These networks are hierarchical with a dense network at a low network level and a coarse network at a high level. Furthermore, the transit vehicles operating at the lower level have a lower travel speed than the vehicles at the higher level. While the main leg of a multimodal trip is often at the high network level, the access and egress legs are mostly at a low level. According to the study of Van Nes (2002), a scale factor of 3 between two network levels should be applied. For the operational speed, the scale-factor is at least 1.67. At a hierarchical perspective, the bike operates at the lowest network level. Therefore, it should have a high network density to increase accessibility. The BTM vehicles will operate at a mid-level and the train at a high level.
When looking at a specific infrastructure or transit line corridor, several different types of multi-level transit services can be applied. Three of these services are an express-, zone-, and trunk-feeder system. With the bike as access and egress, the low- and high transit levels can have much fewer stops. The most suitable service system is dependable of the application scenario. The express and trunk-feeder systems seem mostly suitable for longer corridors, while the zone system is also applicable for shorter distances. However, the zone system will function less optimal if the traveller demand is more equally distributed along the line.

3 THEORETICAL APPLICATION

In the literature study, information was obtained and the first three sub-questions were answered. Next step is to combine this information into application of multimodal networks with the bicycle as core. However, multiple bicycle catchment radius values and (multilevel) transit service outlines are suggested. Furthermore, the effects of catchment radius values in combination with (multilevel) transit service outlines on the travel time and accessibility are unknown. Therefore, the following sub-questions are formulated:

"What are the effects of the combined bicycle catchment radius and (multilevel) transit services on the travel time and accessibility?"

"Which applications of multimodal networks with the bicycle as core are suitable to implement in a network"

To answer these sub-questions, several experiments will be made divided into three scenarios called: 'Corridor', '2D Corridor', and 'Mobili-City'. The first two scenarios will focus on answering the first sub-question. The Mobili-City scenario is used to answer the second sub-question. A more detailed description about the setup of the scenarios is found in sub-chapter 3.2. Before starting with the experiments, it is needed to know how-to design a multimodal network with the bicycle as core. This is discussed in sub-chapter 0.
After completing the experiments, preliminary conclusions can be made. Also a first indication about the feasibility of succeeding the (sub-)goals can be given.

3.1 DESIGN STRATEGY

To design a multimodal network with the bicycle as core, a design strategy is needed. But how should this strategy should look like? In the literature study, the bicycle catchment radius values were determined. These values can be used as base in the design strategy. By using catchment areas, suitable locations for new BTM stops, train stations and P+R can be determined. With this method, the bicycle use of travellers determines how the transit network will be organized. However, there are some factors making it more complicated. For short distances, the full trip can also be done by bicycle (door-to-door bicycle trip). It is debatable if multimodal trips should "compete" with door-to-door bicycle trips. Instead, they should fill each other weaknesses. So, promote or focus on d-t-d bicycle trips when the distances are small, and use multimodal trips for the longer trip distances.
While new train stations can be introduced, the existing stations should not be ignored. As new train stations can be expensive (depending on size and functions), it is preferred to use/improve existing train stations than construct new-, and remove existing stations.
Based on the description above, a design strategy is made. In Figure 22, this strategy is shown consisting of 5 steps. As the d-t-d cycling and multimodal trips should not compete with each other, the first step focus on d-t-d trips between residential- and high demand zones. A residential zone represents a neighbourhood or a small village, and high demand zones areas with a lot of commercial- and/or educational activity. Especially during the rush hours, a lot of commuting travelling occurs between these zones. If the travel distance is not too large, the focus should be on optimizing the bicycle routes between the zones. By optimizing these routes, the travel time can be decreased and is a multimodal trip not needed.
The next step is to optimize bicycles routes to existing train stations from residential zones within cycling distance. This will not only save travel time for travellers from these zones, but also prevents the need of a Bus/Tram/Metro (BTM) connection to the train station. For bicycle as egress mode, the catchment area is used to draw bicycle routes from train stations or P+R to high demand zones.

After completing the first two steps, it is known which residential zones do not need a multimodal trip for travelling to the high demand zones and/or train station. The other zones will need a BTM connection or an extra train station. Based on the catchment areas of travellers using the bicycle, suitable locations for BTM stops and train stations are determined in step 3. To save costs, new train stations can only be placed at existing train tracks. Furthermore, it is preferred to limit the number of new BTM stops and train stations, to save costs, dwell[IV] time and decelerations of the vehicle.
With the known locations of the new BTM stops and train stations, the BTM service line routes can be determined in step 4. The main priority of these service lines is to transport the travellers to the high demand zones and train stations. The new train stations can be implemented into the existing train schedules. During the design of BTM lines, it is preferred to limit the number of transit lines and detours.
In the last step, the multimodal network is finalized where the network is smoothened. This could be connecting separate bicycle paths to make the bicycle network one interconnected network.

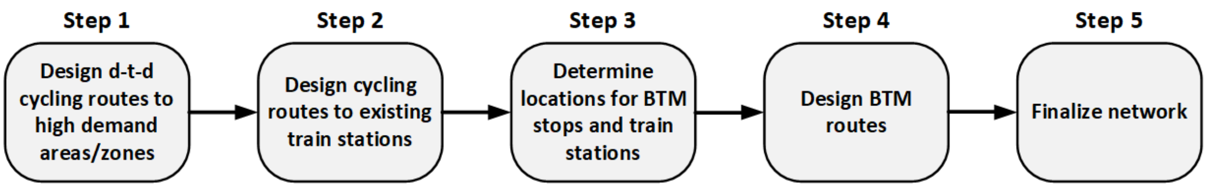


Figure 22 Design strategy

To visualize the design strategy, a small example is made and shown in Figure 23. This simplified example is based on typical Dutch urban areas. The black nodes represent residential zones and the red node a high demand zone. The grey nodes are transfer stations like train stations or P+R stations. Furthermore, a highway and a train track are present. On a daily base, a lot of commuting travellers living in the residential zones are travelling to the high demand zone or the train station. Furthermore, travellers from other areas travel to the high demand zone by using the car or train as main travel mode.
In the first step, the catchment area of the high demand zone for door-to-door bicycle trips is drawn. For the residential zones within this area, bicycle routes to the high demand zone are drawn. Also these zones do not need a multimodal trip for travelling to the high demand zone. In the example, three residential zones are close enough for door-to-door trips.
In the second step, the catchment areas of the train stations and P+R are drawn. For the residential zones within the catchment area of at least one train station, bicycle routes to these train stations are drawn. If the high demand zone is within the catchment area of a train station or P+R, bicycle routes are drawn to this zone. In the example, six residential zones are within the catchment area of at least one train station. Furthermore, the high demand zone is also within the area of one train station. Between these zones and the stations, bicycle routes are drawn and do not need a BTM connection for trips to the train station.
For the zones in need of a BTM connection, BTM stops are placed in the third step. In the example one extra BTM stop is sufficient as the zones outside the catchment radius of the BTM are close to a train station. Based on the locations of the high demand zone, train stations, BTM stop and P+R, a BTM line is designed in the fourth step. The final step is smoothening the bicycle infrastructure network. In Figure 24, the final travel routes between the residential zones and the high demand zone or train stations are shown.

[IV] The amount of time a transit vehicle stand still at a stop or station

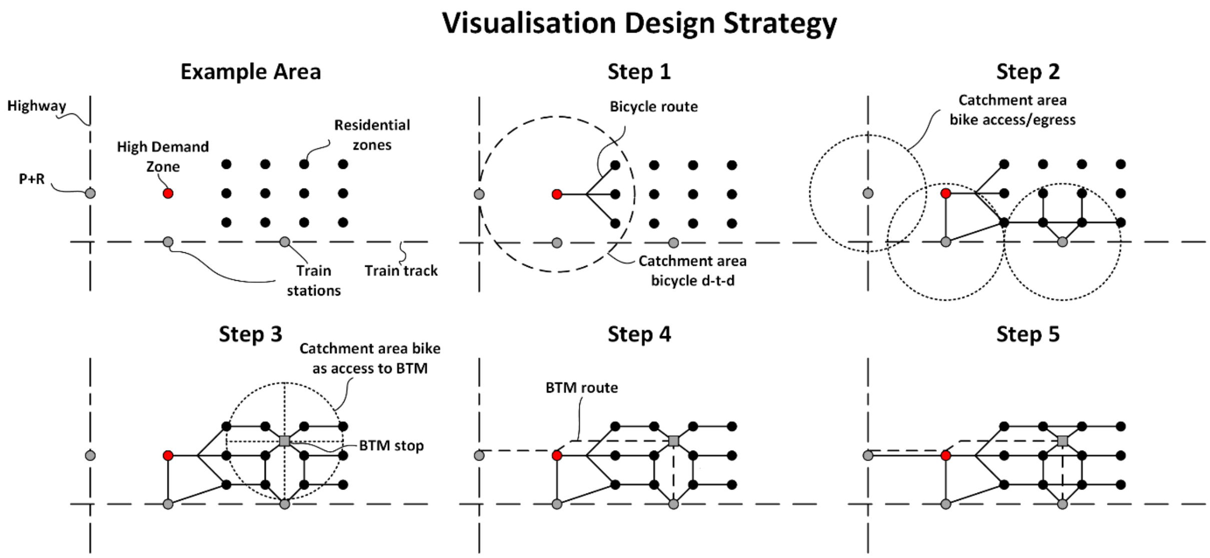


Figure 23 Example design strategy

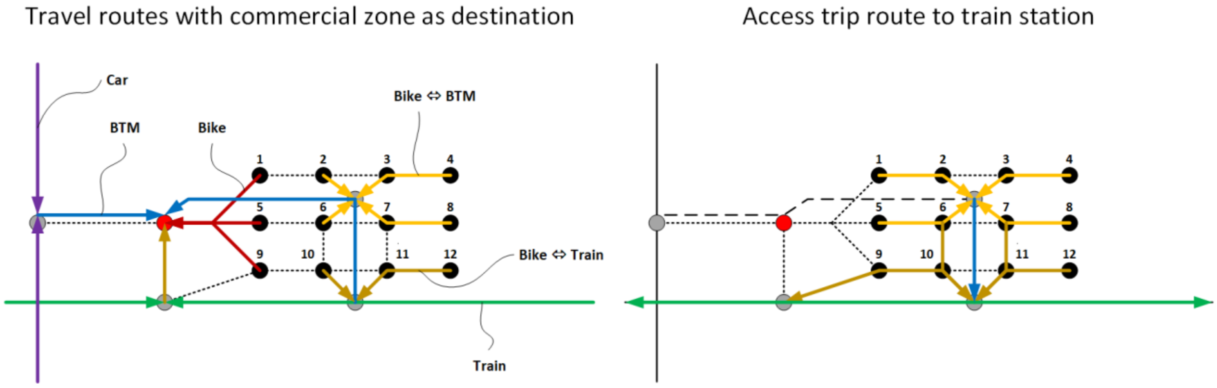


Figure 24 Travel routes

3.2 Setup Scenarios

As stated, the experiments consist of three scenarios are called: Corridor, 2D Corridor, and Mobili-City. The first two focus only on the relationship between the catchment radius of the bicycle and the (multilevel) transit services. In the last scenario, the first designs of bike-based multimodal networks are made, with the design strategy as a tool. To perform experiments, a simple setup with a high "playability" is preferred. With a simple setup, studying the effects of certain applications becomes easier. Furthermore, it should be easy to make changes in the calculations and setup.

Eventually it is chosen to use a combination of Microsoft Excel and -Visio. The calculations of the experiments will be done in Excel. In Visio, the calculation results can be visualised by connecting it to Excel. To keep the experiments and programming simple, the networks in each scenario consist of links and nodes. The nodes represent a certain neighbourhood in a city or a stop/station/P+R. The links are infrastructure connections between the nodes.

In all scenarios, the travel demand and link intensity are not considered. Main reason is the higher complexity of programming these aspects into calculations. Furthermore, different setups of travel demand have a high impact on the results. So, all nodes representing a residential neighbourhood have an equal weight. In the USP case study, the travel demand and link intensity will be included.

In all scenarios, the total (experienced) travel time and connection quality for each node are calculated. The calculation of the total travel time includes the travel time on the bike, in the transit vehicle, and the waiting time. The full calculation is shown in eq1. For the experienced travel time, multipliers to incorporate the traveller preferences are added into the formula (eq2). A transfer penalty is added

when the traveller needs to transfer between transit modes. The last calculation focus on the connection quality between an OD. In this thesis the connection quality is determined as the (experienced) travel time per kilometre. OD's with a good connection have a low value, and poor connections a high value. With the connection quality calculation, it is possible to compare zones with different travel distances. In this equation (eq3), the trip time of the fastest trip option is divided by the shortest door-to-door bicycle trip distance. With this equation, trips with a large detour will perform less than trips with a direct route. To compensate lower performance, trips with a detour will need a higher travel speed.
It should be noted that these calculations are relatively simple. For instance, the amount of time needed to park the bicycle and walking time from parking area to platform are left out. However, it is expected that these values are more or less the same for every alternative. Therefore, they can be left out in the calculation. The travel time calculations also assume that travellers arrive random at the transit stop or -station. Therefore, the waiting time is half of the headway time. A precondition of this assumption is that the frequency of the transit line is at least 4x per hour.

$$Total\ Travel\ Time = \sum \frac{l_{cycling\ i}}{v_{cycling\ i}} + \sum \frac{l_{transit\ i}}{v_{transit\ i}} + \sum t_{dwell\ i} * n_{stops\ i} + \sum \frac{60}{f_{transit\ i}} * 0{,}5 \quad (eq1)$$

$$l = travel\ distance\ per\ mode\ (meter)$$
$$v = travel\ speed\ per\ mode\ (meter/min)$$
$$t_{dwell\ i} = dwell\ time\ service\ line\ (\text{min})$$
$$n_{stops\ i} = number\ of\ stops\ during\ trip\ per\ service\ line$$
$$f_{transit\ i} = frequency\ service\ line\ (vehicles/hour\ /direction)^{V}$$

$$Total\ exp.TT = \sum \frac{l_{cycling\ i}}{v_{cycling\ i}} * m_{cycling} + \sum \frac{l_{transit\ i}}{v_{transit\ i}} * m_{transit\ i} + \sum t_{dwell\ i} * n_{stops\ i} * m_{transit\ i} + \sum \frac{60}{f_{transit\ i}} * 0{,}5 * m_{waiting\ time} + P_{transfer} * n_{transfer} \quad (eq2)$$

$$m = multiplier$$
$$P_{transfer} = transfer\ penalty$$
$$n_{transfer} = number\ of\ transfers$$

$$Connection\ Quality = \frac{t_{fastest\ trip}}{l_{d-t-d\ bicycle}} \quad (min/km) \quad (eq3)$$

The multipliers and penalties used in the calculations for the total experienced travel time are based on the values obtained by the literature study, shown in Table 17. For all calculations, the speed values and dwell times are needed.

Table 17 multiplier and penalty values

	Value
Walking time	1,75
Waiting time	1,75
Cycling time	0,75
In-vehicle time BTM low level	1,2
In-vehicle time Train	1
Transfer penalty	5,5 min

The cycling speed on the regular and E-bike are based on the results of the literature study. The other values are based on typical Dutch circumstances. The speed difference between the low and high level BTM services corresponds to the scale factor of 1,67 as advised in the study of Van Nes (2002) as shown in Table 18. In order to check the sensitivity of the results from the calculations, multiple values of the BTM and bicycle are used.

[V] If multiple service lines with exact the same IVT are possible, the frequencies of both lines are summed up

Table 18 speed and dwell time values

	Default	*BTM 30 & 50*	*BTM 40 & 67*	*Bicycle 15*
Walking speed	4 km/h	4 km/h	4 km/h	4 km/h
Cycling speed	12,5 km/h	12,5 km/h	12,5 km/h	15 km/h
Speed E-bike	12,5 km/h	12,5 km/h	12,5 km/h	15 km/h
Speed BTM Low Level	25 km/h	30 km/h	40 km/h	25 km/h
Speed BTM High Level	40 km/h	50 km/h	67 km/h	40 km/h
Speed Train	80 km/h	80 km/h	80 km/h	80 km/h
Dwell time BTM	0,5 min.	0,5 min.	0,5 min.	0,5 min.
Dwell time Train	1 min.	1 min.	1 min.	1 min.

3.2.1 Corridor

The 'Corridor' scenario is made to give more insight into the effects of using different bicycle catchment radius values and (multilevel) transit service outlines on the (experienced) travel time and (experienced) connection quality of the traveller. In the literature study it appeared that the radius value for a BTM stop is very dependable on the quality of the stop and BTM service line. Overall the range of the radius value is 1000 to 2000 m. Furthermore, three main multilevel service systems were identified called: Express, Zone, and Trunk-Feeder.

This 'Corridor' scenario is a one-dimensional (1D) corridor, consisting of 74 nodes with a spacing of 300 m and an internal node spacing of 150 m. Each node, expect the first node, represents a neighbourhood. The first node is a high demand node, where all travellers will travel to.

Based on the earlier mentioned results from the literature study, seven sub-scenarios are created and shown in Table 19 and Figure 25. For each sub-scenario, the catchment radius of the bicycle, multilevel BTM service outline type, frequency and the number of BTM service lines are assigned. Based on the assignment, two alternatives for each sub-scenario are made. The first alternative assumes walking as access mode, and the second the bicycle. In the walking alternatives, the catchment radius is always 400 m (Rijsman, 2018). For each sub-scenario, the (experienced) travel time and (experienced) connection quality results from both the walking- and cycling alternative are compared. These comparisons will indicate if a bicycle-transit combination decreases the (experienced) travel time compared to a walking-transit combination. Another comparison is made between the results of all cycling alternatives. This comparison is used to identify which bicycle catchment radius value and (multilevel) transit service outline seems most suitable to apply.

Table 19 sub-scenarios Corridor Scenario

Sub-scenario	*Catchment Radius bicycle*	*Multilevel BTM*	*Frequency*	*# of Service lines*
Traditional 4x	1000 m	No	4x	1
Traditional 8x 1000 m	1000 m	No	8x	1
Traditional 8x 2000 m	2000 m	No	8x	1
Traditional Asymmetric	1000 - 2000 m	No	8x	1
Express 4x	1000 m (LL) or 2000 m (HL)	Yes, Express	4x	2 (1 LL, 1 HL)
Zone 4x	1000 m (LL) or 2000 m (HL)	Yes, Zone	4x	3
Trunk-Feeder 4x	1000 m (LL) or 2000 m (HL)	Yes, Trunk-Feeder	4x	3 (2 LL, 1HL)

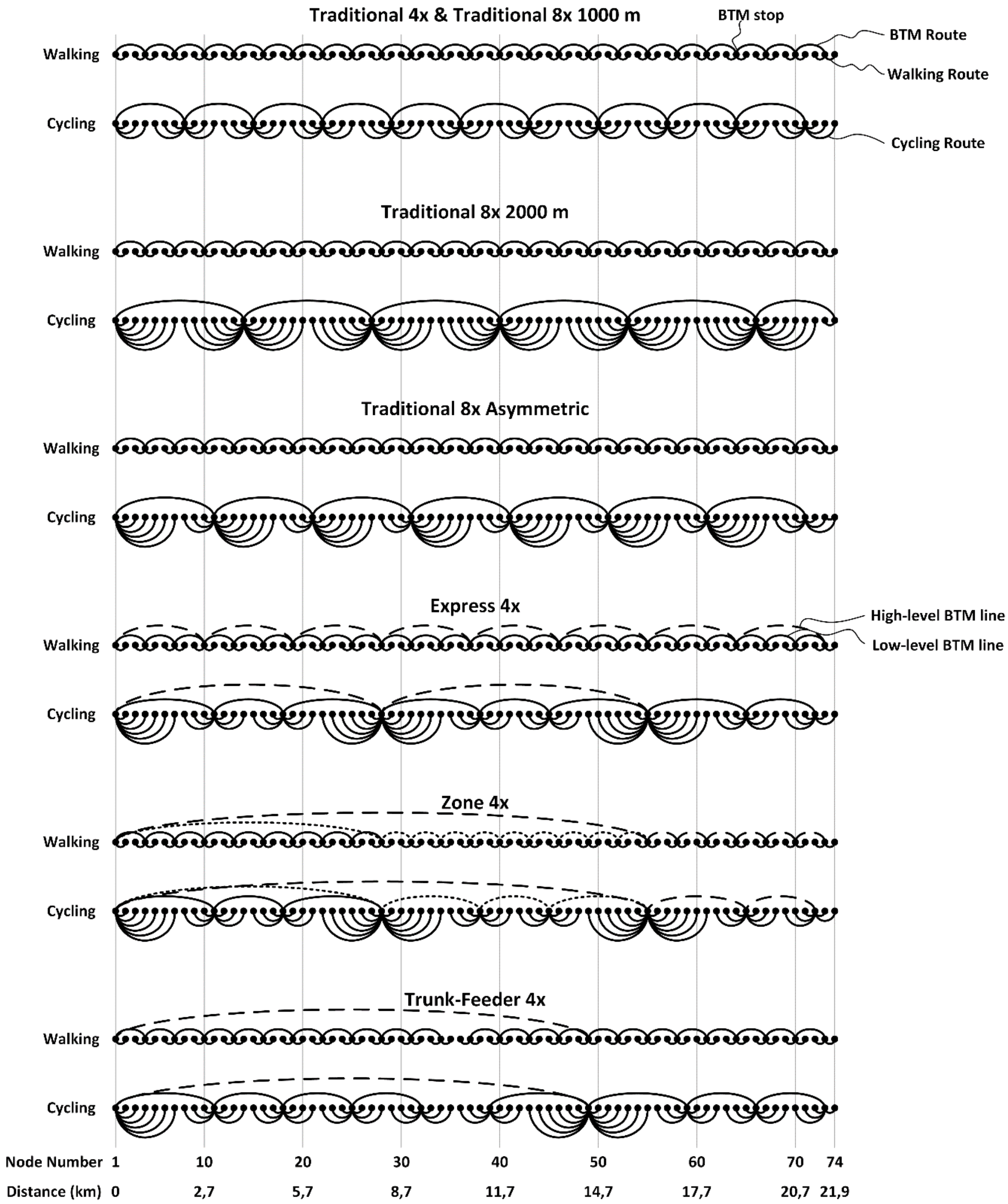


Figure 25 Design Alternatives Corridor Scenario

The first four sub-scenarios have only a one-level BTM service and differ in the applied bicycle catchment radius value and BTM frequency. By comparing the cycling alternatives of these four sub-scenarios, the effect of the bicycle catchment radius on the total (experienced) travel time and (experienced) connection quality can be studied. The cycling alternatives of the first three sub-scenarios use a circular catchment area for BTM stops. The cycling alternative of the fourth sub-scenario has an 'asymmetric' catchment area. In this alternative, cyclists travel only up to 1000 m to a BTM stop if it is located in the opposite direction of the destination (travelling 'upstream' to the BTM stop). If the BTM stop is located in the same direction as the destination (travelling 'downstream' to de BTM stop), the catchment radius is 2000 m. This sub-scenario is created after the first (experienced) travel time results, discussed in 3.3.1., were studied.

The other three sub-scenarios have a multilevel BTM service systems. As these sub-scenarios have multiple BTM services, each service line will have a frequency of 4x per hour. Using a frequency of 8 would require much more BTM vehicles in these sub-scenarios, compared to the sub-scenarios with a traditional BTM service outline. This can be seen as an unfair advantage for the sub-scenarios with a multilevel transit service outline. In the last three sub-scenarios, there are BTM service lines operating at a low level network and/or at a high level network. The 'high level' BTM vehicles operate at a higher travel speed with a stop distance three times higher than the 'low level' BTM (van Nes R. , 2002). According to the literature study, the catchment radius of the BTM stop is also dependable of the transit quality. 1000 m if the quality is low and 2000 m for high quality BTM stops. Therefore, the BTM stops connected to a low-level BTM service will have a catchment radius of 1000 m, and 2000 meter if also connected to a high-level BTM service.
While seven sub-scenarios are made, dozens of other options were possible. However, it is assumed that it is be possible to answer the sub-question with these sub-scenarios. Adding more sub-scenarios would not add extra value to this study.

After completing the Corridor scenario, it should be possible to make first statements about the effects of bicycle catchment radius values and (multilevel) transit service outlines on the (experienced) travel time and (experienced) connection quality. The results of this scenario will be used in the 2D Corridor scenario.

3.2.2 2D Corridor

The Corridor scenario only examined a network from a 1D view. However, transport networks are structured in 2D and the conclusions from the Corridor scenario may be invalid in a 2D plane. To validate these conclusions, the scenario 2D Corridor is made.
In Figure 26, the outline of the second scenario is shown. In the area, a couple of dozen nodes are spread out. The in-between node distance is now 1000 m and the internal node distance 200 m. It is assumed that all travellers from each node want to travel to destinations outside this area. Unlike the previous scenario, the BTM services now have a frequency of 6 vehicles per hour per direction for all alternatives. As the destination for all travellers is outside the area, all BTM service lines will end at 1000 m outside the area.
The alternatives applied in this scenario are based on the results of the previous 1D scenario. To compare the alternatives with walking, a walking alternative is also made. Also for this scenario, the catchment radius of walking is 300 m. Therefore, every node needs a BTM stop. In the next sub-chapter, de outlines of the alternatives are described.

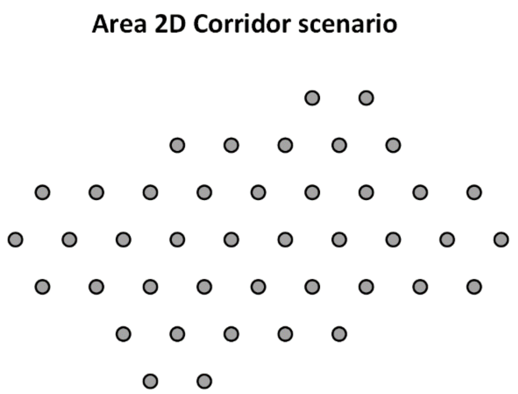


Figure 26 Area 2D corridor scenario

Like in the previous scenario, the total (experienced) travel time and the connection quality are calculated. In the connection quality formula, a small adaption is made for this scenario. Instead of the door-to-door bicycle distance, the total travel distance for each node in the walking alternative is used. Main reason is the absence of a door-to-door bicycle distance values. With the results of these calculations and the findings of the previous scenario, a conclusion about the validation of the previous scenario results can be made. Another addition in this scenario are the investment- and operational cost of BTM services in the area. These costs are based on the service line length, number of stops, frequency and maintenance. In Table 20, the used costs values are shown. The costs for the metro are based on a mix of underground and ground level trajectories. The stop costs of the metro is based on ground level stops. For this study, only the cost difference between the alternatives are relevant. As the difference in bicycle infrastructure costs is likely much smaller, these costs are not considered.

Table 20 Cost values in euro's (Brogt, 2019)

	Bus	*Tram (*	*Metro*
Track (€ per km)	2.000.000	10.000.000	70.000.000
Stop (€ per stop)	450.000	450.000	450.000
Vehicle (€ per veh)	300.000	1.500.000	2.000.000
Track Maintenance(€ per km)	85.000	500.000	850.000

After completion of the 2D Corridor scenario, it should be possible to give a preliminary answer to the sub-question: *"What are the effects of the combined bicycle catchment radius and (multilevel) transit services on the travel time and accessibility?"*. Furthermore, the results of the first two scenarios will indicate which bicycle catchment radius values and (multilevel) transit lines are most beneficial for the traveller. This information will be used in the 'Mobili-City' scenario.

3.2.3 Mobili-City

With the results of the first two scenarios, sufficient input is created designing multimodal networks with the bicycle as core. Combined with the findings of the literature study and the design strategy the first designs can be made. Based on the obtained information and results, different applications of multimodal networks with the bike as core are possible. To study the possible applications and to test the design strategy, another scenario called "Mobili-City" is made. In this scenario, several design alternatives based on different applications of bike-based multimodal networks are made. The main goal is to find multimodal networks with the bicycle as core which have the potential for application in the case study. Furthermore, the design strategy will be tested.

In Figure 27, the outline of the area is shown. The area is a simplified representation of an urban area with several characteristics. It consists of commercial- and residential nodes, a train track with two train stations, and a highway with a P+R station. Between the residential- and commercial nodes, the in-between distance is 1000 m. The internal distance in these nodes is 250 m. During the design process, the existing infrastructure and station will not be changed. Furthermore, no extra P+R or train stations are added.

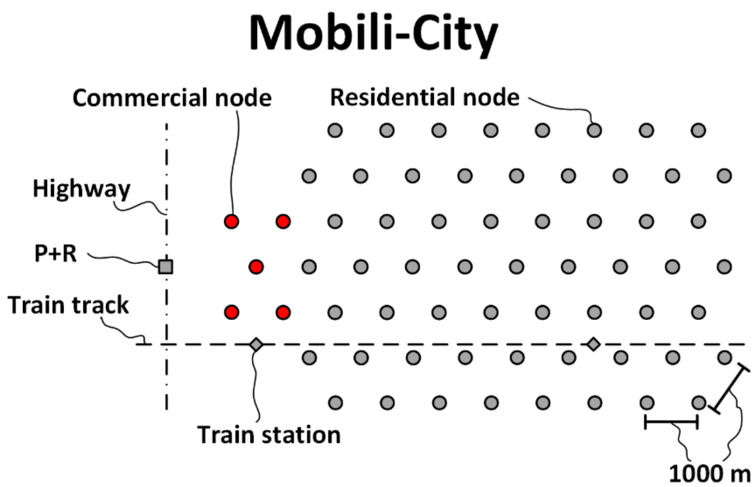


Figure 27 outline Mobili-City scenario

The Mobili-City scenario considers three main groups of travellers. The first group are travellers from residential nodes, travelling to the commercial nodes. The second group also starts at the residential nodes, but goes to a train station (no station preference). From the train station, they travel to a destination in a different region. The travellers from the last group originate from outside the area to have the commercial nodes as final destination. These travellers enter the area by car or train and travel via the P+R or train station to the commercial nodes. As the travellers from the second group have a different destination, two simulation types will be done. In the first simulation, trips to the commercial nodes are considered. Trips to a destination outside the area are simulated in the second simulation.
Unlike the previous scenarios, the Mobili-City scenario also includes E-bike and shared-bike. For door-to-door and access trips, the traveller will use the regular bike or E-bike. The shared-bike can only be used as egress trip. The catchment radius of these bicycle trips will be based on the findings of the literature study and the results of the two previous scenarios. Also for the Mobili-City scenario a cost calculation is done.

With the design strategy tool, several alternatives of multimodal network with the bicycle as core are designed. During the design process, the bicycle and BTM infrastructure are implemented. After completion of the design process, the most attractive travel option for the travellers can be determined. It is likely that between an OD, multiple travel options are present. To determine which travel option is most attractive to the travellers, the total (experienced) travel times are calculated. Based on these results, the most attractive travel option for each OD is determined. The travel tims are used to calculate the connection quality. Combined with the costs of each alternative, a first conclusion about the effectiveness of the designed alternatives can be made. Based on these conclusions, the potential of different applications can be determined. In the next sub-chapter, the results of all experiments are described.

3.3 RESULTS

In the previous sub-chapter, the setup of the experiments are described. The next paragraphs describe the results of the experiments.

3.3.1 Corridor

Walking vs. Cycling

The comparison between walking and cycling is shown in Tables 21 & 22 and Figures 28 & 29. A more extended overview is shown in the Appendix(Ax 1 and 2). In Table 21, the average decrease of the total (experienced) travel time per node using eq 4 is shown. The table also shows the relative decrease of the total (experienced) travel time for all nodes combined using eq 5. Last, the tables show the number of nodes with a faster or slower total (experienced) travel time compared to the walking alternative.

$$Average\ travel\ time\ difference\ per\ node = \frac{\sum\left(tt_{walking\ i} - tt_{cycling\ i}\right)}{n_{total\ nodes}}\ (eq\ 4)$$

$$Relative\ travel\ time\ difference = \frac{\sum tt_{walking\ i} - \sum tt_{cycling\ i}}{\sum tt_{walking\ i}} * 100\%\ (eq\ 5)$$

According to Table 21, all cycling alternatives created a lower total travel time compared to walking. This difference was even more clear when comparing the total experienced travel time. Depending on the sub-scenario, several nodes have a longer travel time with the cycling alternative compared to the walking alternative. An interesting observation is the large differences in results for the Traditional 8x 1000 m, 2000 m, and Asymmetric sub-scenario. Since the walking alternatives for these sub-scenarios are exactly the same, the difference is caused by the catchment radius of the bicycle. Between these three, the Asymmetric sub-scenario scores best with the highest travel time decrease and least nodes with a slower travel time. To explain the cause of this difference, Figure 28 is made. In this figure, the total travel time values per node for the walking- and the three cycling alternatives are plotted. In this figure, all plots have a distinctive wave pattern. The alternatives with a large catchment radius have fewer, but larger waves than the ones with short catchment radius. The nodes with a BTM stop are located at the bottom of a wave. The top of the waves consist of nodes located furthest of a BTM stop. For all cycling alternatives, the nodes assigned to a BTM stop located 1 km or further upstream scored often worse compared to walking. This explains why the cycling alternative for the Traditional 8x 2000 m sub-scenario scored less than the other two sub-scenarios. This is also clearly visible in Figure 28, as it has peaks high above the plot of the walking alternative. The figure also shows the reason for the advantage of the asymmetric radius over the to 1000 m radius as for the 1000 m cycling radius, more stops are needed (11 vs. 8). Therefore, more nodes are assigned to a BTM stop upstream of the corridor.

Also for the sub-scenarios with multilevel transit services, the cycling alternatives decreased the total (experienced) travel time for most nodes. However, a significant number of nodes had an increase of the total travel time. This is most noticeable for the Express sub-scenario. Main cause it the presence of less high level BTM stops in the corridor. Therefore, less nodes are directly connected to a high level service. Eventually, the nodes with a direct connection to a high level service in the walking alternative but without one in the cycling alternative, score less.

Table 21 Total (Experienced) Travel Time results compared to walking-transit

Sub-Scenario	Total Travel Time				Total Experienced Travel Time			
	Delta node eq 4 (min)	Delta eq 5 (%)	# Nodes Faster	# Nodes Slower	Delta node eq 4 (min)	Delta eq 5 (%)	# Nodes Faster	# Nodes Slower
Traditional 4x	4,9	11,4	67	6	9,5	16,8	69	4
Traditional 8x 1000 m	4,4	11,3	66	7	8,3	16,5	69	4
Traditional 8x 2000 m	4,0	10,3	59	14	9,0	17,8	66	7
Traditional 8x Asymmetric	5,0	12,7	69	4	9,6	19,0	70	3
Express 4x	2,3	6,8	48	25	8,8	16,9	56	17
Zone 4x	3,1	9,5	58	13	7,7	17,5	62	9
Trunk-Feeder 4x	5,8	15,3	61	12	13,1	23,5	65	8

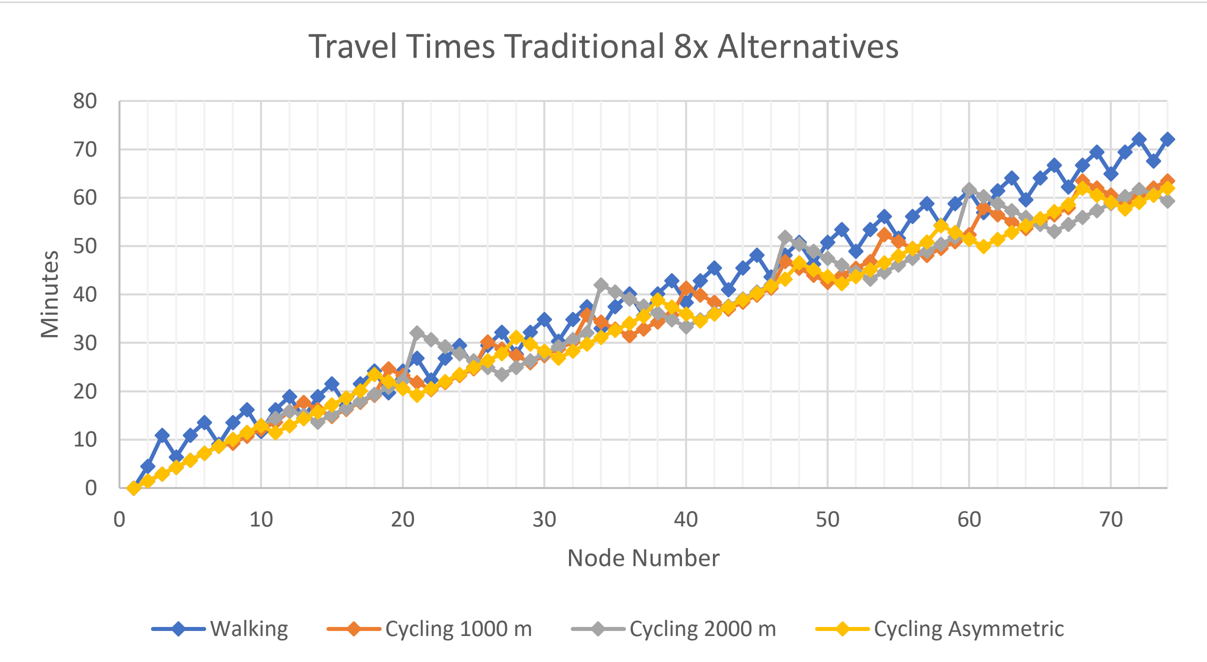


Figure 28 Travel time values per node traditional 8x alternatives

The results of the connection quality are shown in Table 22. Like with the travel times, the connection quality improved for all cycling alternatives with around 1 min/km. This difference is even higher for the experienced travel time. Between the three Traditional 8x sub-scenarios, the is smaller. To compare them, Figure 29 is made. In this figure, the min/km value for every node with the three cycling alternatives and the walking alternative is shown. Also in this figure, a wave pattern can be observed. Several nodes close to the destination have a lower connection quality with the cycling alternatives, compared to the walking alternatives. For longer trip distances, the quality is rarely worse for the cycling alternative.
Figure 29 also shows the negative impact of travelling upstream to a BTM stop compared to downstream. Especially for the cycling alternative with a 2000 m catchment radius, these negative effects are visible. However, the difference is smaller for longer travel distances.

Table 22 Connection Quality results

Sub-Scenario	Average Connection Quality				Average exp Connection Quality			
	Walking (min/km)	Cycling (min/km)	Delta (min/km)	Delta (%)	Walking (min/km)	Cycling (min/km)	Delta (min/km)	Delta (%)
Traditional 4x	5.0	3.80	1.2	24	7.1	4.50	2.6	37
Traditional 8x 1000 m	4.3	3.47	0.9	20	6.0	4.06	1.9	32
Traditional 8x 2000 m	4.3	3.53	0.8	19	6.0	3.92	2.1	34
Traditional 8x Asymmetric	4.3	3.43	0.9	21	6.0	3.92	2.1	34
Express 4x	4.4	3.38	1.0	24	7.1	4.19	2.9	41
Zone 4x	4.3	3.19	1.1	25	6.3	3.73	2.5	41
Trunk-Feeder 4x	4.7	3.46	1.3	27	7.1	4.20	2.9	41

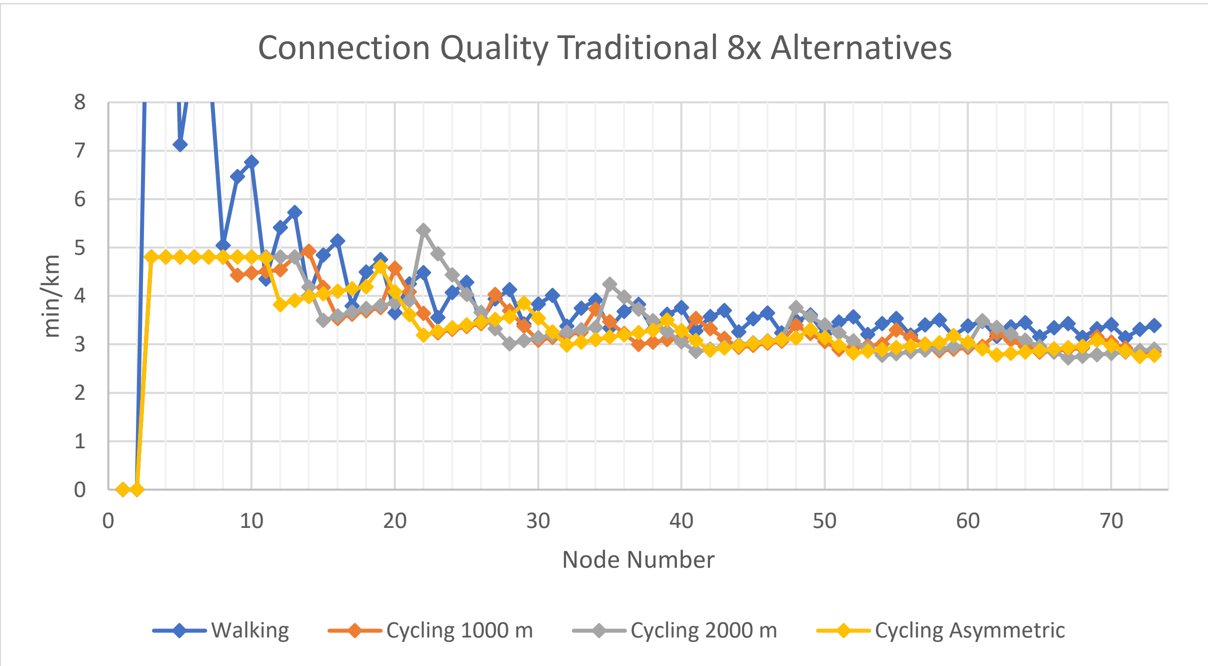


Figure 29 Connection quality per node traditional 8x alternatives

Based on the results shown in tables 21 & 22 and the figures 28 & 29, a preliminary conclusion can be drawn. Overall, the results suggest that using a bike-BTM combination improves both the total (experienced) travel time and the (experienced) connection quality for a full 1D corridor compared to the walk-BTM combination. However, this improvement does not apply for traveller from all nodes. Several nodes score even worse in a cycling alternative compared to a walking alternative. Most of these nodes were assigned to a BTM stop located at 1 km or more upstream in the corridor. But, the negative impact is smaller for longer trip distances. Based on these observations, it can be concluded that the maximum catchment radius for cycling to a BTM stop upstream should be 1 km. A higher cycling

distance will give a too negative impact on the total (experienced) travel time and (experienced) connection quality.
The results also indicate the benefit of applying a catchment radius of 2000 m for BTM stops downstream. The cycling alternatives "2000 m" and "Asymmetric" need fewer BTM stops than the "1000 m" alternative. This lowers not only the in-vehicle time of in a BTM vehicle, but also the number of nodes assigned to a BTM stop upstream. Based on these observations, applying an asymmetrical catchment radius (1000 m for BTM stops upstream and 2000 m downstream) for traditional transit services seems most suitable. Also for the sub-scenarios with multilevel services, the cycling alternative creates an overall improvement in the (experienced) travel time and connection quality.

Cycling vs Cycling
In the previous sub-paragraph, a comparison between the walking- and cycling alternatives of each sub-scenario was made. However, a comparison between the cycling alternatives of each sub-scenario is still needed. In order to do this, the cycling alternative of sub-scenario Traditional 4x is used as a reference. The results are shown in Tables 23 & 24 and Figures 30 up to 33. An extended overview of the results is shown in the Appendix(Ax 3 and 4).
In Table 23, the same outline as Table 21 is used. Overall, all other cycling alternatives scored higher than the cycling alternative of the Traditional 4x sub-scenario. But, large differences between the alternatives can be found. For the average total travel time difference per node, the multilevel alternatives scored much better than the traditional alternatives. However, the Express 4x and Trunk-Feeder 4x alternatives scored worse regarding experienced travel time. Only the Zone 4x scored higher for both regular- and experienced travel time.
It is also noticeable that in the cycling alternatives of sub-scenarios Traditional 8x 2000 m, Express 4x, and Trunk-Feeder 4x, many more nodes have a slower travel time. To further understand the pattern, Figure 30 & 31 are made. In these graphs, the (experienced) travel time difference per node for each sub-scenario are plotted. It shows that some alternatives have more extreme fluctuations than other alternatives. Especially the three alternatives from the earlier called sub-scenarios fluctuate highly. Due to the large fluctuations, multiple nodes have a slower total (experienced) travel time. The cause of these fluctuations differ per sub-scenario. For the Traditional 8x 2000 m sub-scenario, the likely cause is the large cycling distance to an upstream BTM stop. The likely cause of the fluctuations for the Express 4x and Trunk-Feeder 4x sub-scenario is the extra transfer between the low- and high level BTM. The extra transfer created a lot of extra waiting time (7,5 minutes). Apparently, the high level service is not fast enough to compensate this.

Table 23 Difference Total (Experienced) Travel Time compared to Traditional 4x

Sub-Scenario	Total Travel Time				Total Experienced Travel Time			
	Delta node (min)	Delta (%)	# Nodes Faster	# Nodes Slower	Delta node (min)	Delta (%)	# Nodes Faster	# Nodes Slower
Traditional 8x 1000 m	3,2	8,4	66	0	5,2	11,0	62	4
Traditional 8x 2000 m	2,8	7,4	49	13	5,8	12,4	55	7
Traditional 8x Asymmetric	3,7	9,9	60	5	6,4	13,6	62	3
Express 4x	6,0	15,8	51	11	4,0	8,5	44	18
Zone 4x	8,7	23,1	57	5	10,8	22,9	58	4
Trunk-Feeder 4x	5,9	15,6	50	12	4,8	10,2	48	14

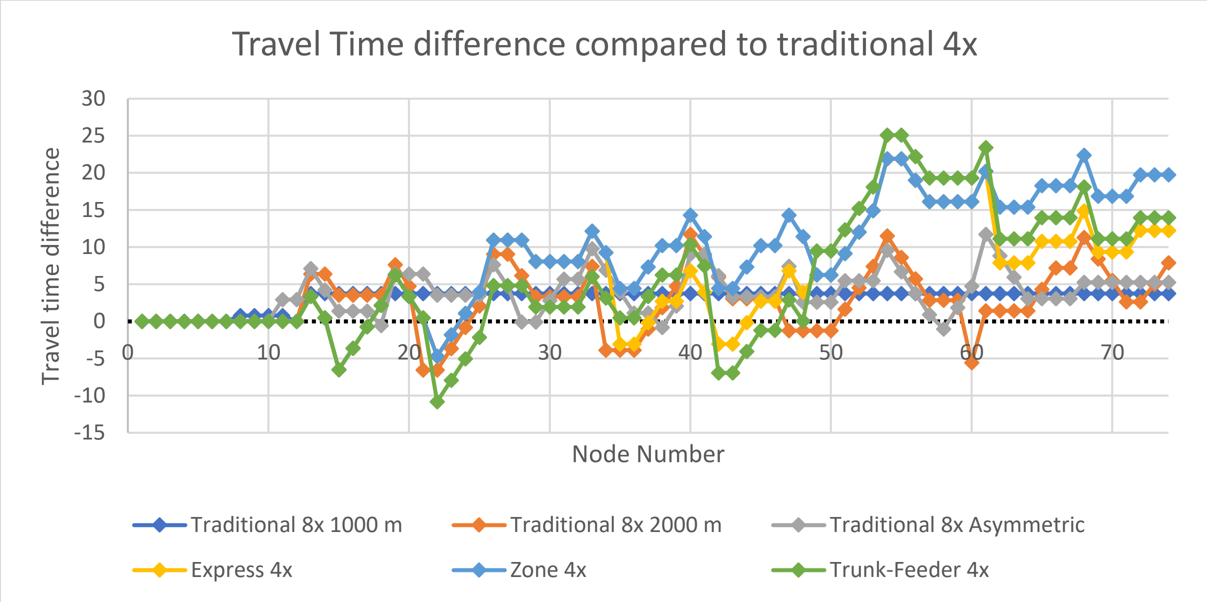


Figure 30 Travel time difference between cycling alternatives

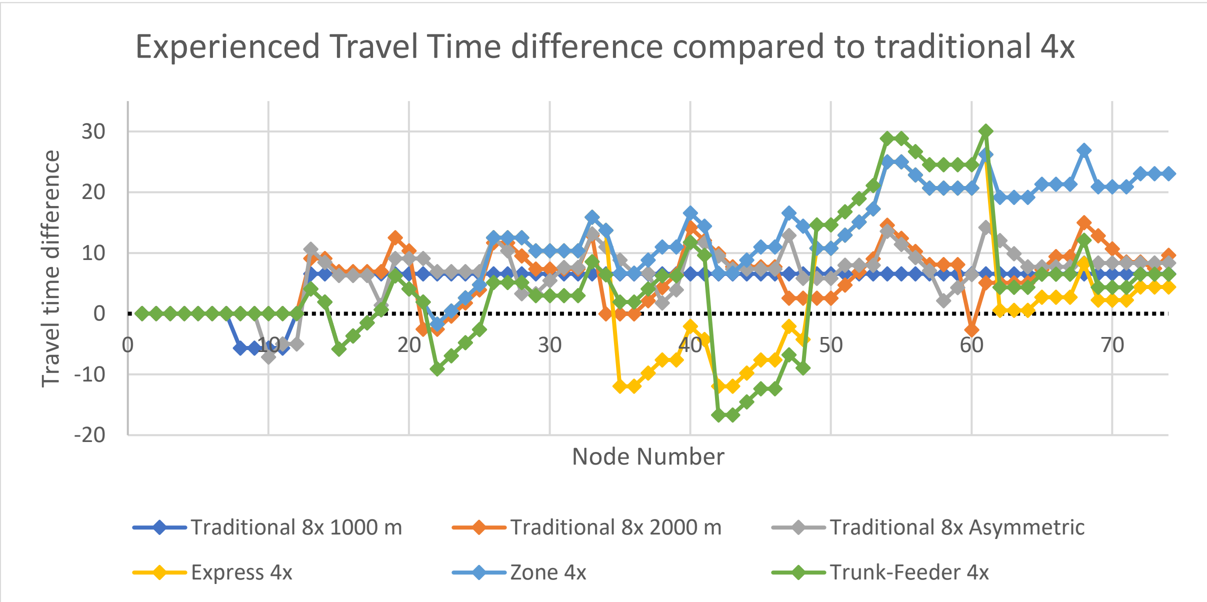


Figure 31 Experienced travel time alternatives between cycling alternatives

In Table 24, the connection quality are shown. Furthermore, Figure 32 & 33 show the min/km difference for each node. The differences in the connection quality are much smaller. Only exception is the Zone 4x, which has a significant higher connection quality than the other alternatives. Like with the total experienced travel time, the Express 4x and Trunk-Feeder 4x score worse for the experienced connection quality. The cause of this decrease in connection quality is shown in Figure 32 & 33. Like with the (experienced) travel time, these and the Traditional 6x 2000 m sub-scenarios have many fluctuations. These fluctuations become smaller when the distance between the nodes increases. Another interesting observation is the result of the Traditional 8x 2000 m. While the score for the average connection quality is poor, it has one of the highest values for the experienced connection quality. This is likely caused by the low multiplier value for cycling. As the share of cycling in the total travel time is relatively high for this sub-scenario, calculating the experienced travel time results in a good score.

Table 24 Connection Quality results compared to Traditional 4x

Sub-Scenario	Average Connection Quality			Average exp Connection Quality		
	Average (min/km)	Delta (min/km)	Delta (%)	Average (min/km)	Delta (min/km)	Delta (%)
Traditional 8x 1000 m	3,47	0,33	8,8	4,06	0,43	9,6
Traditional 8x 2000 m	3,53	0,27	7,1	3,92	0,57	12,8
Traditional 8x Asymmetric	3,43	0,38	9,9	3,92	0,58	12,9
Express 4x	3,38	0,42	11,1	4,19	0,31	6,8
Zone 4x	3,19	0,61	16,0	3,73	0,77	17,1
Trunk-Feeder 4x	3,46	0,34	9,1	4,20	0,30	6,6

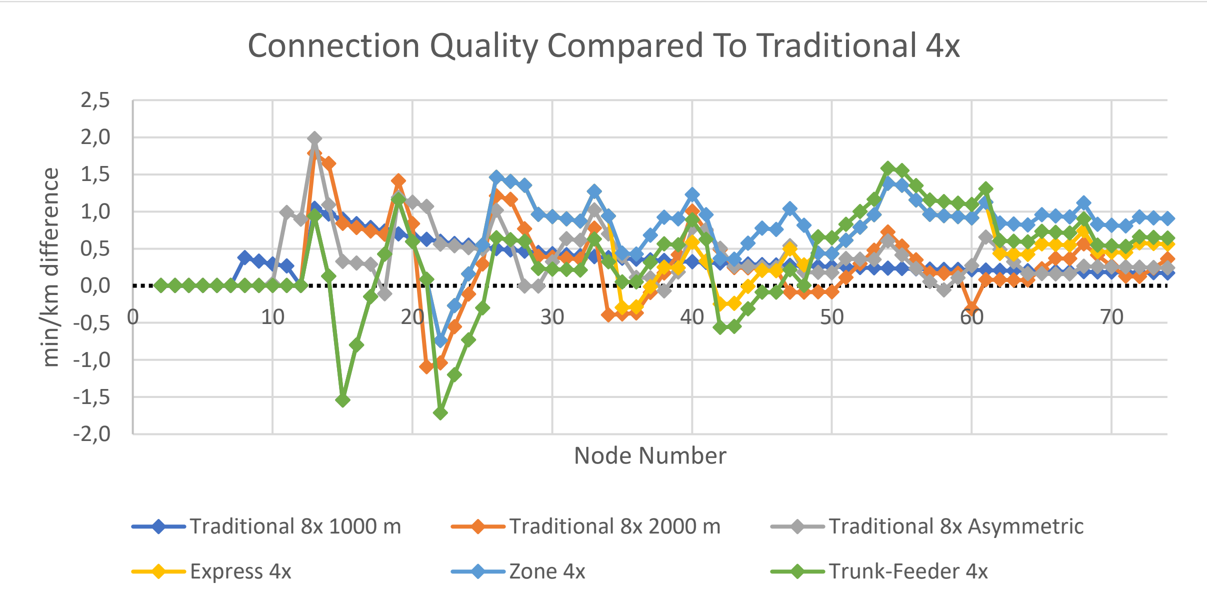


Figure 32

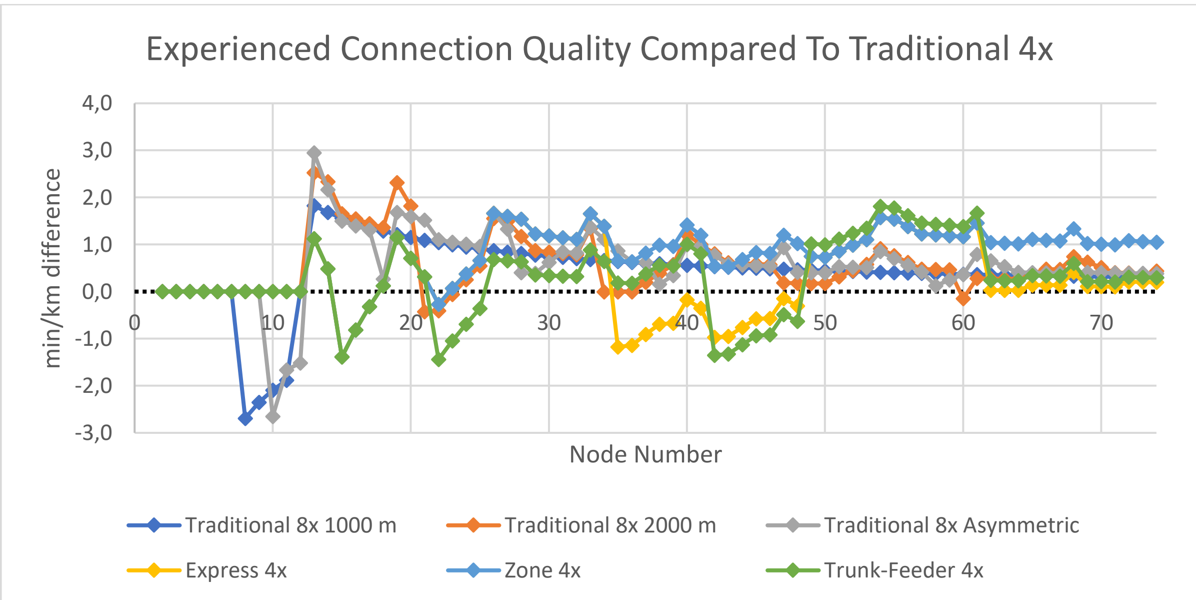


Figure 33

The comparisons of all cycling alternatives gave different insights in the results of the total (experienced) travel time and connection quality. The results suggest that alternatives can score very differently when incorporating experience multipliers. Especially the results of the Traditional 8x 2000 m, Express 4x, and Trunk-Feeder 4x are noticeable. While having the poorest score for both travel time and connection quality, the cycling alternative of the Traditional 8x 2000 m scored much higher after incorporating the travel experience factor. For the Express 4x and Trunk-Feeder 4x, it was the other way around. Furthermore, the Trunk-Feeder 4x also had a low score for the connection quality. Main cause of the low results after implementing the experience factor is the extra transfer needed between the two BTM levels. As the waiting time has a high multiplier (1,75x) and a transfer a penalty of 5,5 min, an extra transfer will result in a strongly increased experienced travel time. The other three sub-scenarios have a much more constant score. Overall, the cycling alternative of the Zone 4x sub-scenario has the best score. While not having the best results, the Traditional 8x Asymmetric is relatively constant.

Sensitivity Results

As discussed in the sub-chapter Setup Scenarios, a small sensitivity analysis will be done. In this analysis different speed values of the BTM and bicycle are applied. These values can be found in Table 18. Some results of the analysis are shown in the Tables 25 to 30. A full overview of the results is shown in the Appendix(Ax 5 up to 12).

The first two tables are the sensitivities of the walking vs. cycling results. Table 25 shows the effects of changing speed values on the average difference of the travel time per node and the relative decrease of the aggerated total travel time. In Table 28, the amount of nodes having a faster or slower travel time compared to walking after changing the speed values is shown. Overall, mostly small changes occur. For most sub-scenarios, the average difference per node in minutes decreases. However, the relative difference for the aggregated travel time increases for all sub-scenarios. So, the difference between the walking- and cycling alternatives becomes larger in relative terms but smaller in absolute terms. When increasing the cycling speed, all cycling alternatives have an improvement in both absolute and relative terms. The effects of changing the speed values on the experienced travel times and connection quality are shown in the appendix. In these tables, a same pattern can be found.

Overall, changing the speed values do not have a large impact on the comparison between walking and cycling. Therefore the conclusions made in the Walking vs. Cycling paragraph are still valid.

Table 25 Sensitivity travel time difference walking vs. cycling results

	Default		BTM 30 & 50		BTM 40 & 67		Cycling 15	
Sub-Scenario	min	%	min	%	min	%	min	%
Traditional 4x	4,9	11,4	4,8	12,4	4,6	14,1	5,4	12,7
Traditional 8x 1000 m	4,4	11,3	4,3	12,5	4,3	14,6	4,9	12,6
Traditional 8x 2000 m	4,0	10,3	3,9	11,3	3,8	12,9	4,9	12,4
Traditional 8x Asymmetric	5,0	12,7	4,7	13,7	4,5	15,4	5,6	14,5
Express 4x	2,3	6,8	2,3	7,6	2,5	9,2	3,0	8,8
Zone 4x	3,1	9,5	2,8	10,0	2,5	10,2	3,7	11,7
Trunk-Feeder 4x	5,8	15,3	5,3	15,6	4,8	16,2	6,5	17,1

Table 26 Sensitivity number of nodes with a faster or slower travel time

	Default		BTM 30 & 50		BTM 40 & 67		Cycling 15	
Sub-Scenario	Faster	Slower	Faster	Slower	Faster	Slower	Faster	Slower
Traditional 4x	67	6	66	7	67	6	68	5
Traditional 8x 1000 m	66	7	64	9	65	8	68	5
Traditional 8x 2000 m	59	14	59	14	58	15	62	11
Traditional 8x Asymmetric	69	4	65	8	65	8	70	3
Express 4x	48	25	49	24	50	23	52	21
Zone 4x	58	13	55	16	55	16	58	13
Trunk-Feeder 4x	61	12	61	12	60	13	61	12

The Tables 27 up to 30 show the sensitivity of the cycling vs. cycling results. Table 27 and 28 have the same outline as Table 25. Table 27 shows that changing the BTM operational speed has different impacts on the traditional- and multilevel sub-scenarios. For the traditional sub-scenarios, the average difference in travel time per node does not change much. But, they have a significant improvement for the relative difference of the aggerated total travel times. For the multilevel alternatives, changing the BTM operational speed has a negative impact. For all values, the difference with the Traditional 4x sub-scenario becomes smaller. When applying a BTM speed of 40- (low-level) and 67 km/h (high-level), the Traditional 8x Asymmetric sub-scenario scores even better than the Express 4x and Trunk-Feeder 4x. Increasing the cycling speed to 15 km/h has a positive impact for almost all sub-scenarios. Only for the Traditional 8x 1000 m sub-scenario, the values are more or less the same.
The results in Table 28 with the experienced travel time show a same, but also more extreme pattern. For the Express 4x, the difference with the reference almost disappears when applying a BTM operational speed of 40- and 67 km/h. Also for the Trunk-Feeder 4x, the difference is small.
In Table 29, the sensitivity of the number of nodes with a faster or slower travel time is shown. Overall, no large changes occur. In most cases, an increase or decrease of one or two nodes occur. Main exception is the Trunk-Feeder 4x. When applying a BTM speed of 40 and 67 km/h, 4 more nodes have a slower travel time. When using the experienced travel time (Table 30), the differences become (much) larger. For the Express 4x, increasing the BTM operational speed has a negative impact. The number of nodes with a slower experienced travel time even become higher than the number of nodes with a faster travel time. Also for the Trunk-Feeder 4x, many nodes will have a slower experienced travel time compared to Traditional 4x. For the Traditional 8x 2000 m, the effects are much more positive. It is the only sub-scenario with a significant increase of nodes with a faster experienced travel time.
In the Appendix (Ax 11 and 12), the sensitivities of the connection quality are shown. The effects of changing the travel speed on the connection quality are comparable with the above discussed results. Therefore, the sensitivity of the connection quality is not discussed.

Table 27 Difference total travel time compared to Traditional 4x with different speed values

	Default		BTM 30 & 50		BTM 40 & 67		Cycling 15	
Sub-Scenario	min	%	min	%	min	%	min	%
Traditional 8x 1000 m	3.2	8.4	3.2	9.6	3.3	11.7	3.1	8.4
Traditional 8x 2000 m	2.8	7.4	2.8	8.3	2.8	9.9	3.1	8.3
Traditional 8x Asymmetric	3.7	9.9	3.6	10.9	3.5	12.5	3.9	10.4
Express 4x	6.0	15.8	5.1	15.3	3.4	12.2	6.1	16.4
Zone 4x	8.7	23.1	7.8	23.4	6.2	21.9	8.9	23.8
Trunk-Feeder 4x	5.9	15.6	5.0	15.0	3.5	12.5	6.0	16.2

Table 28 Difference total experienced travel time compared to Traditional 4x with different speed values

	Default		BTM 30 & 50		BTM 40 & 67		Cycling 15	
Sub-Scenario	min	%	min	%	min	%	min	%
Traditional 8x 1000 m	5.2	11.0	5.2	12.4	5.2	14.6	5.5	11.7
Traditional 8x 2000 m	5.8	12.4	5.7	13.6	5.7	16.0	6.0	12.9
Traditional 8x Asymmetric	6.4	13.6	6.3	15.0	6.2	17.2	6.6	14.1
Express 4x	4.0	8.5	2.7	6.4	0.7	1.9	4.1	8.8
Zone 4x	10.8	22.9	9.5	22.5	7.5	20.9	10.9	23.3
Trunk-Feeder 4x	4.8	10.2	3.5	8.3	1.7	4.8	4.9	10.5

Table 29 Number of nodes having a faster or slower travel time compared to Traditional 4x with different speed values

Sub-Scenario	Default		BTM 30 & 50		BTM 40 & 67		Cycling 15	
	Faster	Slower	Faster	Slower	Faster	Slower	Faster	Slower
Traditional 8x 1000 m	66	0	66	0	67	0	62	0
Traditional 8x 2000 m	49	13	50	13	52	11	49	13
Traditional 8x Asymmetric	60	5	63	2	62	3	61	3
Express 4x	51	11	53	11	52	12	51	11
Zone 4x	57	5	59	5	58	6	57	5
Trunk-Feeder 4x	50	12	51	13	48	16	50	12

Table 30 Number of nodes having a faster or slower experienced travel time compared to Traditional 4x with different speed values

Sub-Scenario	Default		BTM 30 & 50		BTM 40 & 67		Cycling 15	
	Faster	Slower	Faster	Slower	Faster	Slower	Faster	Slower
Traditional 8x 1000 m	62	4	62	4	62	5	62	0
Traditional 8x 2000 m	55	7	59	4	60	3	59	3
Traditional 8x Asymmetric	62	3	62	3	62	3	62	2
Express 4x	44	18	41	23	31	33	44	18
Zone 4x	58	4	58	6	57	7	58	4
Trunk-Feeder 4x	48	14	48	16	36	28	48	14

The sensitivity analysis gave some interesting insights about the effects of changing the speed values on the results. For the comparison between walking and cycling, changing the speed values only had a small impact on the results. The effects were much greater for the comparison between the cycling alternatives. For the Express 4x and Trunk-Feeder 4x, increasing the BTM operational speed had a large negative impact. When applying a BTM speed of 40 and 67 km/h, they have almost no improvement compared to the reference sub-scenario (Traditional 4x).

Conclusion Corridor scenario

In this paragraph, the results of the corridor scenario were described and discussed. The main goal of this scenario was to study the effects of bicycle catchment radius and (multilevel) transit services on the total (experienced) travel time and connection quality. Furthermore, two questions were stated. These were: "*Does a bicycle-transit combination improve the total (experienced) travel time and connection quality compared to walking*" and "*Which combinations of bicycle catchment radius and (multilevel) transit services are interesting to apply"*. During these experiments, several different bicycle catchment radius and transit services were combined and applied into a 1D corridor of approximately 20 km with 74 nodes. Eventually, 7 sub-scenarios with each a walking- and a cycling alternative were made.

First, comparisons between the walking- and cycling alternatives were made. For each sub-scenario, the results showed an improvement of the total (experienced) travel time and connection quality with the cycling alternative. But, this does not apply for every node. For each sub-scenario, a couple of nodes have a worse travel time and connection quality with the cycling alternative. Still, the results indicate that a bicycle-transit combination improve the total (experienced) travel time and connection quality.

The walking vs. cycling section was also used to study the effects of the bicycle catchment radius on the total (experienced) travel time and connection quality. As the Traditional 8x 1000 m, -2000 m, and -Asymmetric have the same walking alternative, differences between these three are caused by the bicycle catchment radius. Based on the comparison between these three, several observations are made. It appeared that using a catchment radius of 2000 m had a negative impact on the results. Especially the nodes located more than 1 km downstream of their BTM stop had negative results. This makes sense as first travelling upstream costs "double". Based on this observation, the maximum bicycle catchment radius for nodes downstream of a BTM stop should be 1000 m. Another observation were the significant better results for the Asymmetric catchment radius compared to the other two. It

had not only a lower average travel time, the number of nodes with a slower travel time was also very low. Apparently, a catchment radius of 2000 m for nodes located upstream of a BTM stop has a positive effect on the total (experienced) travel time and connection quality.
In the next part, the cycling alternatives of each sub-scenario were compared. The cycling alternative of the Traditional 4x sub-scenario was used as reference. For this comparison, the effects of (multi-level) transit services were also studied. It created a wide range of different results. Furthermore, the score changed a lot when using the experience multipliers. This was most noticeable for the Traditional 8x 2000 m, Express 4x, and Trunk-Feeder 4x. The Traditional 8x 2000 m had a poor score for the regular travel times, but a good score when using experienced travel time. For the Express 4x and Trunk-Feeder 4x, it was the other way around. Furthermore, these three had much more nodes with a lower travel time. Overall, the cycling alternative of the Zone 4x sub-scenario had the best score in all aspects. While not the best, the Traditional 8x Asymmetric often scored above average.
Besides only comparing the results, a sensitivity analysis was done. In this analysis, the speed values of the BTM and cyclist were changed. For the comparison between walking and cycling, no large changes were observed. Between the cycling alternatives, the changes were more significant. The Express 4x and Trunk-Feeder 4x were scoring much worse after increasing the BTM operational speed. For the other sub-scenarios, the impact was less significant.

Based on the findings of the Corridor scenario experiments, several basic conclusions can be made. For regular BTM stops, an asymmetric bicycle catchment area (radius of 1000 m for downstream of a stop and 2000 m upstream) has the most positive impact on the total (experienced) travel time and connection quality. Combined with a traditional transit service, it can compete with the multilevel services. Only the Zone 4x has always a better score. Therefore, two bicycle-transit combinations are interesting to apply. The first one is an asymmetric bicycle catchment area (1000-2000 m) combined with one traditional high frequency transit service. The other one are multiple zone-based transit service lines with a catchment radius of 1000 m for low level stops and 2000 m for high level stops. It will depend on the circumstances which one is more suitable. As the scenario consisted of an 1D corridor, the validity of the made conclusion are still uncertain. Therefore, a check with a 2D corridor is needed.

The results from this scenario have some implications for the design strategy. During the description of this strategy in sub-chapter 3.1, a circular bicycle catchment area was assumed. With an asymmetric catchment area, some small changes are needed. Firstly, an asymmetric catchment area for BTM stops have to be drawn. The drawing of this area is also dependable on the location of the destination. If there are multiple main travel directions, this can become complicated. In the Mobili-City scenario, it will be further discussed.
The results of this scenario also indicated the inefficiency of applying an express and trunk-feeder transit service system. Therefore, the transit lines should be more designed according to a traditional or zone based transit line system. While the zone based approach has better results, it is more difficult to apply as it depends on the location and the number of stops/stations. Eventually, the choice will depend on the outline of the area and the locations of the stops/stations.

3.3.2 2D Corridor

As stated in the previous sub-chapter, the 2D Corridor scenario consists of a 2D plane with 42 nodes. Furthermore, the destinations of the travellers are outside of the area. This scenario is used to check the validity of the catchment radius conclusions in the previous scenario. In the Corridor scenario, a bicycle radius of 1000 m, 2000 m, and asymmetric (1000-2000 m) were applied. Of these three, the asymmetric catchment area created the most improvement of the total (experienced) travel time and connection quality. For this 2D Corridor scenario, the question is if the asymmetric catchment area is still more effective than the other two.

Alternatives

For this 2D Corridor scenario, 4 cycling alternatives and one walking are developed. In Figure 34, the designs of all alternative are shown. Like with the previous scenario, a node represents a zone and the links infrastructure. In the walking alternative, a BTM stop is present in all nodes. As all cycling alternatives only have a few number of stops, only the traditional transit service is used. In the design, the goal was to connect all nodes to at least one BTM stop and minimize the number of BTM stops. In two alternatives, a catchment radius of 2000 is applied. Main difference are the number of transit lines. While the Asymmetric alternative is almost the same as the 1000 m, a couple of nodes have the option to travel 2 km downstream to a BTM stop instead of 1 km upstream. For all alternatives, the total (experienced) travel time and the connection quality are calculated. Furthermore, a sensitivity analysis and a cost calculation are done. The cycling 1k alternative will be used as reference alternative during the comparison of the alternatives.

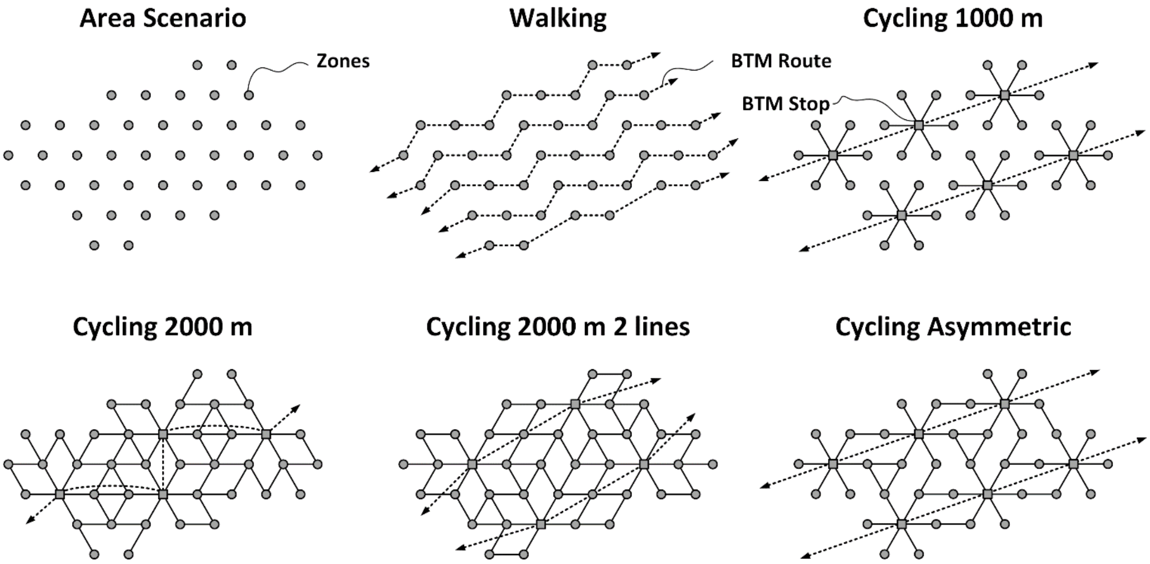


Figure 34 Outlines alternatives 2D corridor scenario

Total Travel time

In Table 31 and Figure 35, the total (experienced) travel time results are shown. Table 31 shows the average travel time, decrease average travel time compared to cycling 1k, and the number of nodes with a faster or slower travel time compared to cycling 1k. Figure 35 shows the travel time of each node, by using a heatmap. The table shows large differences between the alternatives. Only the Asymmetric alternative creates an improvement for both regular and experienced travel time. The other three alternatives score worse than Cycling 1k. With the regular travel time, the Cycling 2k scores even worse than Walking. To better understand the causes of these results, Figure 35 is used. In general, nodes located further from the end of the transit line have a longer travel time. As they often have a longer travel distance, the pattern is logical. Still, some interesting observations can be made. In the Cycling 1000 m and -Asymmetric alternatives with regular travel times, nodes with a travel time higher than 30 minutes are absent. For some nodes in the Walking- and Cycling 2000 m alternatives, the travel time is even higher than 35 minutes.

Between the two alternatives with both a bicycle catchment radius of 2000 m, several differences are present. Overall, the alternative with two lines has a better score than the alternative with one line. But, the heatmap shows that many nodes located at the eastern side of the area score worse. Apparently, the two lines alternative is mostly more suitable for nodes with a longer trip distance.

While the number of BTM stops and its locations is the same, the Cycling Asymmetric alternative scores better than the 1000 m. This is mainly caused by reassign several node to a BTM stop 2 km downstream instead of to a stop 1 km upstream. These nodes have often an improvement of their total travel time. With including the experience factor, the difference becomes larger.

Table 31 Total (experienced) travel time results compared to Cycling 1k alternative

Alternative	Total Travel Time				Total Experienced Travel Time			
	TT Node (min)	ΔTT (%)	# Nodes faster	# Nodes Slower	TT Node (min)	ΔTT (%)	# Nodes faster	# Nodes Slower
Walking	24,5	-14,6	7	35	38,9	-19,3	0	42
Cycling 1k	21,4	-	-	-	32,6	-	-	-
Cycling 2k	25,8	-20,7	6	32	36,9	-13,2	6	32
Cycling 2k 2 lines	24,0	-12,0	12	30	34,6	-6,2	14	27
Cycling asymmetric	20,9	2,3	10	0	31,4	3,6	10	0

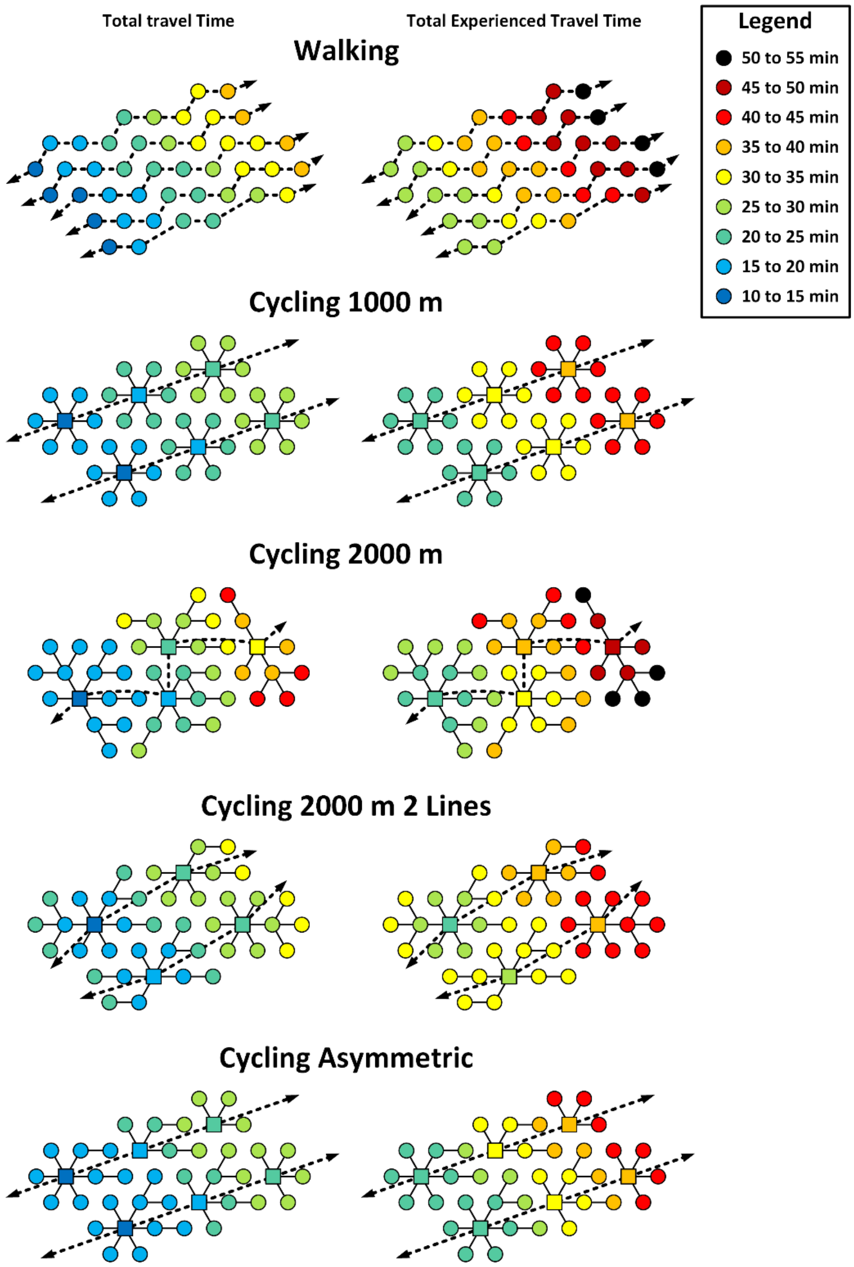


Figure 35 Heatmap Total travel time (left) and Total Experienced travel time (right)

Connection Quality

In Table 32 and Figure 36, the results of the (experienced) connection quality calculations are shown. As with the travel time, the table shows the overall results and the figure several heatmaps. In general, a similar pattern can be found. For most alternatives, the difference with the Cycling 1000 m has become smaller. Only for the Cycling 2k two lines alternative, the difference has become larger. The

Asymmetric alternative has still a better score than the 1000 m, but with a smaller difference. In the heatmaps, nodes at the western side of the area have in general a higher min/km value. The heatmaps also show clearly the negative effects of assigning nodes to a BTM stop upstream. These nodes have often higher min/km values than the other nodes assigned to the same BTM stop. With the Asymmetric alternative, it occurs less often. In all alternatives, the first nodes of each transit line corridor have high min/km values. This is mainly caused by the endpoint of the transit lines at 2 km outside of the area. Therefore, factors like (experienced) waiting time and transfer penalty have a (relative) high impact on the values. If the real destination is much further, the min/km value will be much lower. Still, differences between the alternatives for the first nodes can be found. With the Cycling 2000 m 2 lines alternatives, the min/km values are compared to the other alternatives extremely high. This is caused by assignment to a BTM stop 2 km upstream.

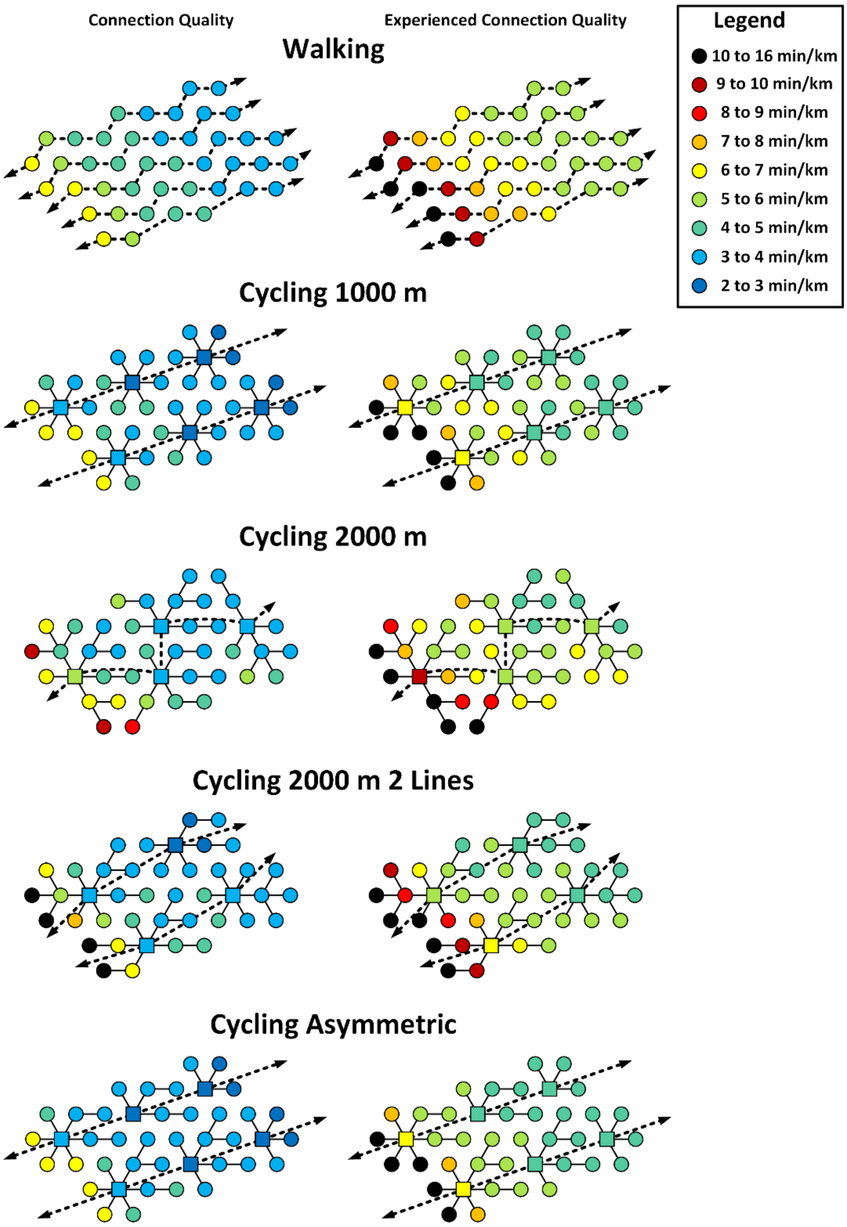


Figure 36 Heatmap Connection quality (Left) and Experienced Connection Quality (Right)

Table 32 (Experienced) connection quality results compared to Cycling 1k

Alternative	**Connection Quality** min/km Node	Δ min/km Node	Δ Node (%)	**Experienced Connection Quality** min/km Node	Δ min/km Node	Δ Node (%)
Walking	4,32	-0,42	-8,9	7,16	-1,07	-17,6
Cycling 1k	3,91	-	-	6,09	-	-
Cycling 2k	4,68	-0,78	-16,6	6,82	-0,73	-11,9
Cycling 2k 2 lines	4,65	-0,74	-15,9	6,75	-0,66	-10,9
Cycling Asymmetric	3,83	0,08	1,7	5,90	0,19	3,0

Sensitivity

Also for this scenario, a sensitivity analysis is made. The outline of this analysis is mostly the same as in the previous one. Only addition is the last sensitivity check, where only 10 vehicles per direction are available for all services combined. This will represent the limited budget of a transit operator. In this scenario, the high level BTM services were absent. Therefore, only the low level BTM operational speed is mentioned. The results of the sensitivity analysis are shown in Table 33 and 34. The results of the (experienced) connection quality sensitivity are shown in the Appendix(Ax 13 and 14). Increasing the operational speed of the BTM improves the total travel time for all alternatives significantly. When using a BTM speed of 40 km/h, the total travel time decreases with around 4.5 minutes. Only Walking has with 5.3 minutes a significant higher decrease. Furthermore, the Asymmetric alternative has only a decrease of 3.6 minutes. It is further noticeable that the Asymmetric score worse than the 1k alternative, when applying a BTM speed of 40 k/h. With the experienced travel time, the Asymmetric has still a better score. Increasing the cycling speed creates the biggest improvement for the last three alternatives. It makes sense as the average cycling distance is longer for these alternatives, than the cycling 1k.

In the results of the last sensitivity check, large differences can be found. As walking has five transit service lines, each line will have a frequency of only 2 vehicles per line and per direction. This has a negative impact in the travel time. In the Cycling 2k alternative, only one transit line is present. Therefore it has a frequency of 10 vehicles. As the other alternatives have a frequency of 5 (two lines), the difference between the Cycling 2k and Cycling 1k alternatives has become much smaller. With the experienced travel time, the Cycling 2k even has a better travel time than the 1k alternative.

With the (experienced) connection quality, similar patterns were found. Therefore, these are not discussed separately.

Table 33 Difference total travel time compared to Cycling 1k with different speed values

Alternative	Default min	Default %	BTM 30 min	BTM 30 %	BTM 40 min	BTM 40 %	Cycling 15 min	Cycling 15 %	10 Vehicles min	10 Vehicles %
Walking	24,5	-14,6	22,2	-13,5	19,2	-11,7	24,5	-18,5	29,5	-31,8
Cycling 1k	21,4	-	19,5	-	17,2	-	20,7	-	22,4	-
Cycling 2k	25,8	-20,7	23,7	-21,1	21,0	-21,8	24,7	-19,4	23,8	-6,3
Cycling 2k 2 lines	24,0	-12,0	22,0	-12,4	19,5	-13,1	22,9	-10,8	25,0	-11,5
Cycling Asymmetric	20,9	2,3	19,3	1,2	17,3	-0,5	20,0	3,3	21,9	2,2

Table 34 Difference total experienced travel time compared to Cycling 1k with different speed values

Alternative	Default min	Default %	BTM 30 min	BTM 30 %	BTM 40 min	BTM 40 %	Cycling 15 min	Cycling 15 %	10 Vehicles min	10 Vehicles %
Walking	38,9	-19,3	36,0	-18,8	32,5	-17,9	38,9	-21,3	47,6	-38,7
Cycling 1k	32,6	-	30,3	-	27,6	-	32,0	-	34,3	-
Cycling 2k	36,9	-13,2	34,3	-12,9	31,0	-12,6	36,0	-12,4	33,4	2,8
Cycling 2k 2 lines	34,6	-6,2	32,2	-6,1	29,2	-6,0	33,8	-5,5	36,3	-5,9
Cycling Asymmetric	31,4	3,6	29,5	2,8	27,1	1,8	30,7	4,1	33,2	3,4

Costs
In this scenario, the costs of transit system for each alternative are also included. For this cost analysis, the construction- & maintenance cost of BTM infrastructure and vehicle costs are taken into account. The costs of implementing a bus, tram, or metro/light-rail are very different. Therefore, the costs for implementing each mode are shown separately. The used cost values are shown in Table 20.
As the Walking alternative has five transit service lines, the cost of implementing a transit system is 2 to 3 times as expensive compared to the other alternatives. The Cycling 2k alternative is by far the cheapest option. The other three alternatives have more or less the same costs. Based on the costs of the transit system, the Cycling 2k alternative is the most attractive alternative to apply.

Table 35 estimated costs per alternative in millions of euros

	Infrastructure			Maintenance			Vehicles		
Alternative	Bus	Tram	Metro	Bus	Tram	Metro	Bus	Tram	Metro
Walking	136	604	4114	5,0	29,3	50	9,0	45,0	60,0
Cycling 1k	40	189	1304	1,6	9,3	16	3,6	18,0	24,0
Cycling 2k	25	119	824	1,0	5,9	10	1,8	9,0	12,0
Cycling 2k 2 lines	38	182	1262	1,5	9,0	15	3,6	18,0	24,0
Cycling Asymmetric	40	189	1304	1,6	9,3	16	3,6	18,0	24,0

Conclusion 2D Corridor scenario
In the 2D corridor scenario, the effects of applying different bicycle catchment radius in a 2D plane were studied. Main goal was to validate the catchment radius observations and conclusions from the Corridor scenario. For this scenario, five alternatives were made called: Walking, Cycling 1k, Cycling 2k, Cycling 2k Two Lines, and Cycling Asymmetric. With these alternatives, the total (experienced) travel time, connection quality, and the costs were calculated. Furthermore, a sensitivity analysis was made. During the comparison of the results, the Cycling 1k alternative was used as reference point.
For both regular and experienced travel time, only the Cycling Asymmetric alternative scored better than the Cycling 1k alternative. But the difference has become much smaller, compared to the results of the previous scenario. Furthermore, both Cycling 2k and Cycling 2k 2 Lines alternatives also scored worse than Cycling 1k when using the experienced travel time. This is conflicting with the results of the previous scenario. In the Corridor scenario, the Traditional 8x 2000 m cycling alternative scored better than the Traditional 8x 1000 m, when using experienced travel time. These observations are also applicable for the (experienced) connection quality results. There are several causes of these differences. First, a likely factor is the outline the 2D plane. The area suited perfectly for the Cycling 1000 m alternative, were each node was assigned to only one BTM stop. It was also not necessary to place these stops at the edges of the area, where they are less effective. For the other three cycling alternatives, it was not possible to prevent it. This has created an advantage for the cycling 1k alternative.
The results also confirm the negative impact of first cycling 2000 m upstream to a BTM stop, observed in the previous scenario. This can be clearly seen in the heatmaps of the connection quality results. According to these maps, the nodes located downstream of their assigned BTM stop (so, travelling upstream with the bicycle to the stop) have always a higher min/km value than the nodes upstream of the same stop. Therefore, this scenario confirms the conclusion about not using a catchment radius of 2000 m for nodes downstream of a BTM stop.
The only design difference between the Cycling 1k, and Cycling Asymmetric alternatives are the assignment of several nodes to a BTM stop 2000 m downstream instead of to a stop 1000 m upstream. This reassignment had a positive impact on both (experienced) travel time and (experienced) connection quality for the nodes. Only when the BTM operational speed is increased to 40 km/h the difference becomes small. These observations confirms the statements and conclusions from the previous scenario about the positive effects of applying a bicycle catchment radius for nodes upstream of a BTM stop.
The calculations costs of implementing the BTM systems showed that the Cycling 2k alternative is much cheaper to apply. Main reason is the presence of only one transit service line. If frequency is

dependant of the number of available vehicles, like in the sensitivity analysis, the Cycling 2k alternative can become the best scoring alternative.

Overall, it can be concluded that applying an asymmetrical bicycle catchment radius also creates the best scores in a 2D plane area. But, the difference with the application of a 1000 m catchment radius has become smaller. Applying a 2000 m catchment radius is only interesting if the decision of an alternative is largely based on the total cost of a transport system.
As the difference between the asymmetric- and 1000 m are relative small, It cannot be said with full confidence that applying am asymmetric catchment area creates the most travel time and connection quality improvement for a certain area. Therefore, both should be considered in the next scenario. For the design strategy, the statements made in the conclusion of the previous scenario still holds.

3.3.3 Mobili-City

The last scenario, called "Mobili-City" is a theoretical city with a large commercial zone. As described in the previous sub-chapter and shown in Figure 37, a highway (with one P+R) and train tracks (with 2 train stations) are present. Unlike the previous scenarios, travellers may travel to the commercial zones (with the middle commercial node as main destination) or a train station. Furthermore, train users from an external area want to travel to the commercial zones. The goals of this scenario are implementing the results of the experiments and findings from the literature into a multimodal network design. Furthermore, the design strategy will be used for the first time. This scenario is also used for another comparison between the cycling catchment radius 1000 m and asymmetric. After finishing this scenario, it should be possible to answer the last sub-question: "*Which applications of multimodal networks with the bike as core are suitable to implement in a network".*
Before continuing with the Mobili-City scenario, readjustments in the design strategy are discussed. After these adjustments, the design of the alternatives is described and the results shown. These results will be discussed in the conclusion.

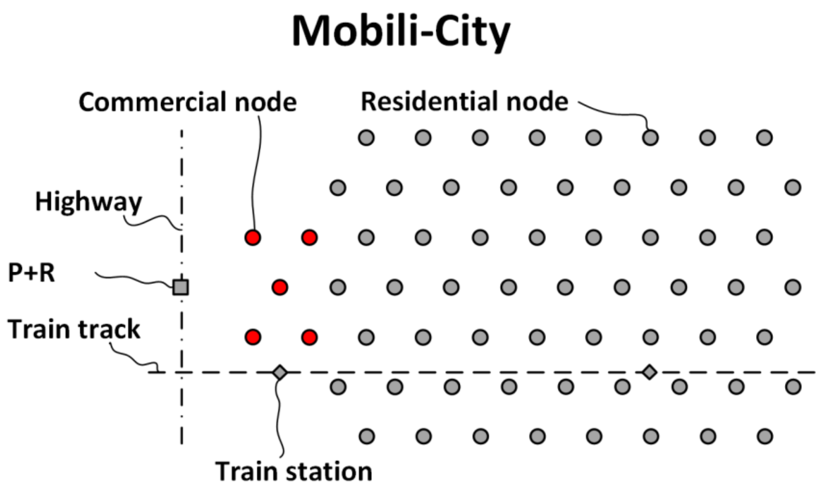


Figure 37 Set-up Mobili-City scenario

Adjustments design strategy

In Sub-Chapter 0, the design strategy was described. A scheme of the steps is shown in Figure 38. The results and conclusions from the first two scenarios indicate the need to specify and adjust some parts of the described design strategy. Especially when applying an asymmetric catchment radius. In the first two scenarios the asymmetric catchment areas had an radius of 1000 m for nodes located downstream of a BTM stop and 2000 m for the ones upstream. For the nodes lying more at the sides of the stop, the catchment radius value is more in a "grey" area. Eventually, it is chosen not to use a hard radius value for these nodes. Therefore, the sketch catchment areas during the design should be more seen as an approximation and not as a hard border.

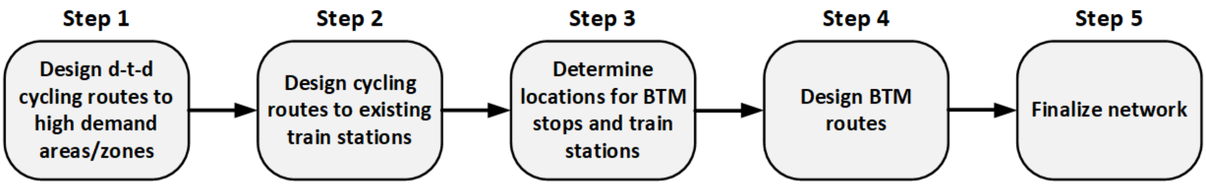


Figure 38 Steps design strategy

In the Mobili-City scenario, the main travel directions are to the commercial zone and train stations. This makes applying an asymmetric catchment area more difficult, as it is dependable on the location of the destination. With multiple destinations, each BTM stop will have several catchment areas, like in Figure 39-Left. As this figure shows, presence of some nodes in a catchment area is dependable on de destination of the traveller from that node. To solve this issue, these nodes need a connection with multiple BTM stations like in Figure 39-Right.

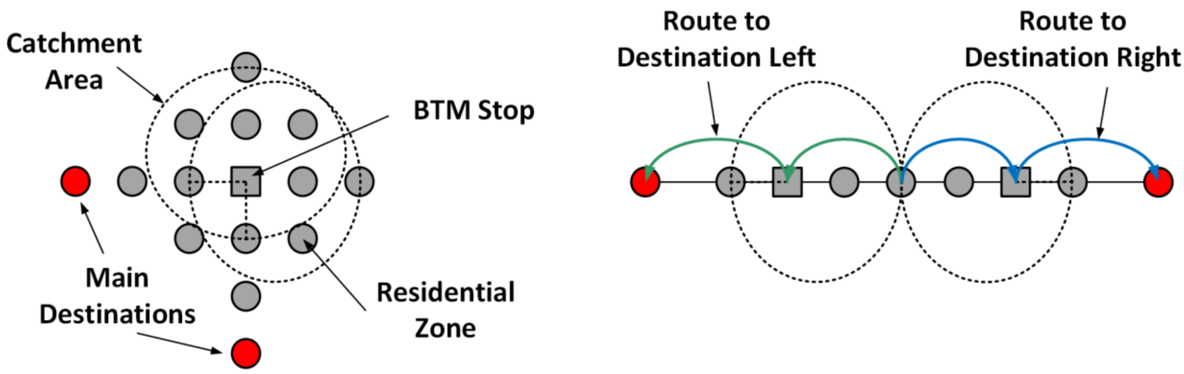


Figure 39 example application asymmetric catchment area in design strategy

In the first two scenarios, only the BTM stops were taken into account. If an asymmetric catchment radius is applied for BTM stops, shouln't it be also applied at train stations? Furthermore, the 2000 m catchment area scored quite poor. However, the travel distances with the train are generally much longer with a higher travel speed. In the results of scenario 1, it can be seen that the negative impact of travelling upstream is less significant for long travel distances (more than 20 km). Therefore, a circular catchment radius for the train station is in general suitable to apply. If the train travel distance is short, an asymmetric catchment radius seems more suitable. Originally, the bicycle catchment radius for train stations was determined at 2500 m. When an asymmetric catchment area is more suitable to apply, a radius combination of 1500-2500 m can be used. This is based on the asymmetric catchment area of the BTM stop.

Design Alternatives

As stated earlier, two alternatives for the Mobili-City area are designed. In the first alternative, a bicycle catchment radius 1000 m for BTM stops is used. For the second alternative, the catchment area is asymmetric. In the literature study, several bicycle catchment radius values were determined. These values are reshown in Table 36. Some of these values are outdated, due to new findings in the previous two scenarios. These are marked with a star. The other values are used during the design of the alternatives.

*Table 36 Catchment radius values from literature study. * means outdated*

	BTM		*Train*		*P+R*	*Door-to-Door*
	Access	Egress	Access	Egress	Egress	
Regular/city bike	*1000-2000 m**	-	*2500 m**	-	-	3500 m
E-bike	*1400-2900 m**	-	*3600 m**	-	-	5000 m
Shared-bike	-	1500 m	-	2000 m	1500 m	-

In Figure 40, the first two steps in the design process are shown. the designs from these steps are for both alternatives. In the first step, the door-to-door bicycle routes to all commercial nodes are designed for residential nodes within the door-to-door bicycle/E-bike catchment area. In the left image of Figure 40, the network design after the first step is shown. For approximately half of the residential nodes, at least one commercial zone is within the door-to-door cycling distance with the bicycle or E-bike. For these nodes, bicycle routes to the commercial nodes are designed. In step two, the bicycle/E-bike access routes to the train stations and egress routes from the P+R are designed. After the first two steps, a first part of the bicycle network is designed.
In the right figure, the catchment area for the bicycle as egress from the P+R and the left station are also shown. It appeared that for the P+R, two commercial nodes are within range and for the left station 3 nodes. For the nodes outside these catchment areas, a BTM connection is needed.

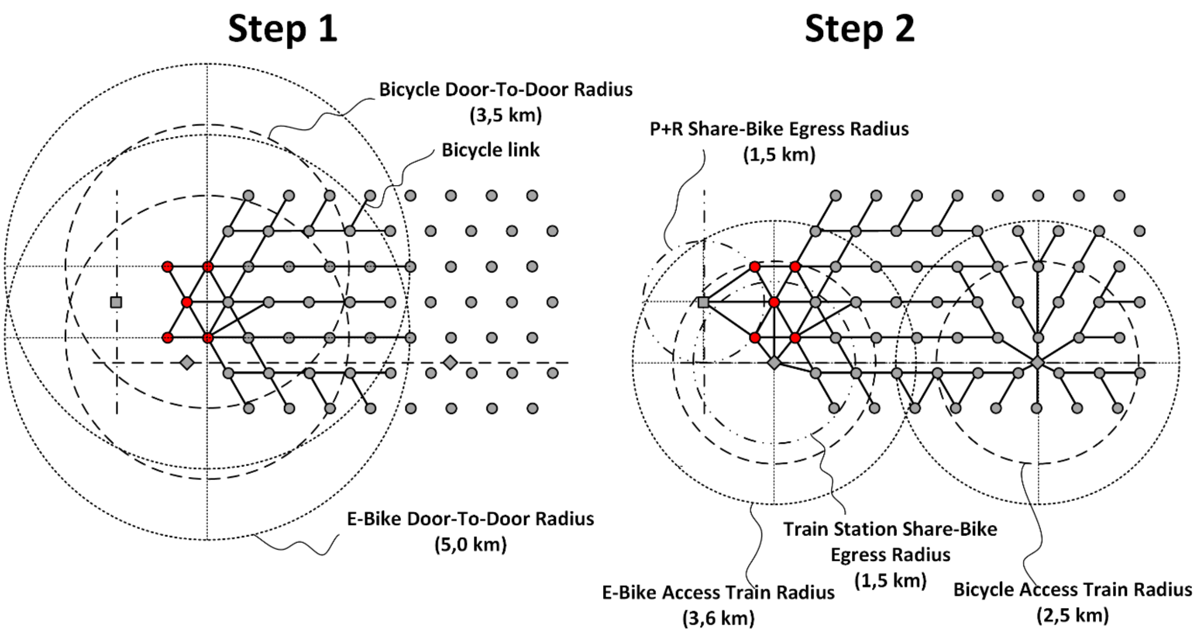


Figure 40 step 1 and 2 of designing the multimodal network for Mobili-City

In the third step, BTM stops are added into the network, for nodes needing a transit link for travelling to commercial nodes and/or train stations. From this step, the designs of the alternatives are different. In Figure 41, the designs of both alternatives after step 3 are shown. Based on the different bicycle catchment radius types, the BTM stops are placed at several nodes. It should be noted that the train stations have also a BTM catchment radius, as they can be used as BTM stop. For the nodes in one or more bicycle catchment areas of BTM stops, bicycle routes to these stops are made. By now, every node has at least one transit connection.
Largest difference between the 1000 m and Asymmetric alternatives are the number of BTM stops. For the 1000 m alternative, 8 extra BTM stops (excluding the stops at transfer stations) are needed while the Asymmetric only needs 5. In the Asymmetric alternative, one BTM stop is next to the train tracks. The trains do not stop at this stop.

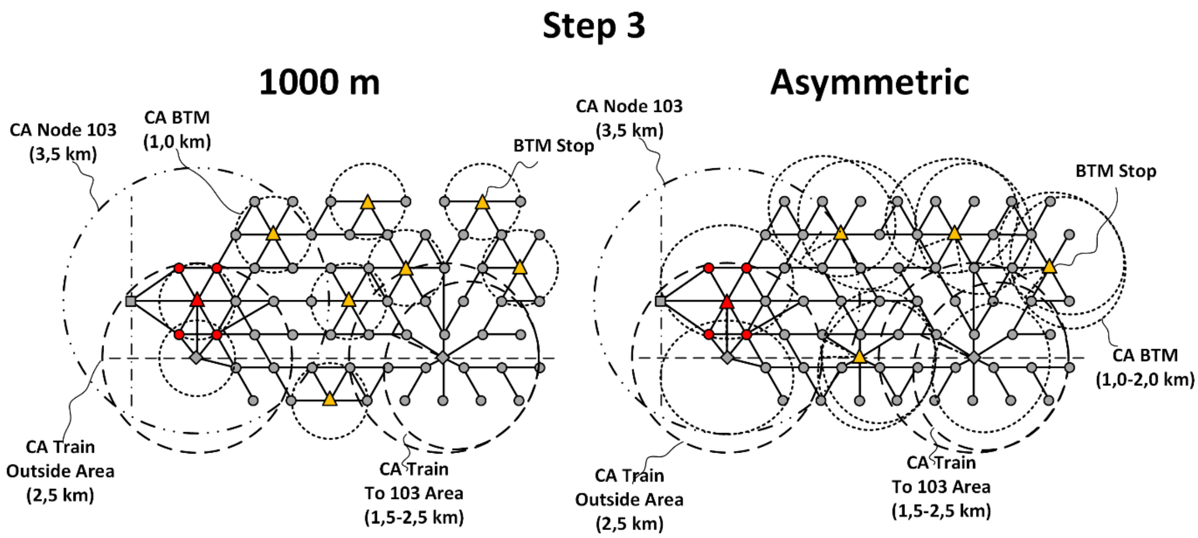


Figure 41 Step 3 with left 1000 m alternative and right the Asymmetric alternative

With the known locations of the BTM stops, the BTM transit service lines can be designed and the bicycle network finalized. In Figure 42, the final multimodal network designs for both alternatives are shown. Each dotted coloured line represents a BTM service line. As travellers want to go to the commercial nodes or a train station, the BTM lines are oriented to these locations. Eventually, the 1000 m alternative has three BTM service lines and the Asymmetric two lines. All lines in both alternatives stop at every stop they pass by. Due to the few amount of stops for every line, a zone-based service line does not seem practical. To finalize the multimodal network, several bicycle links are added to make the bicycle paths more consistent.

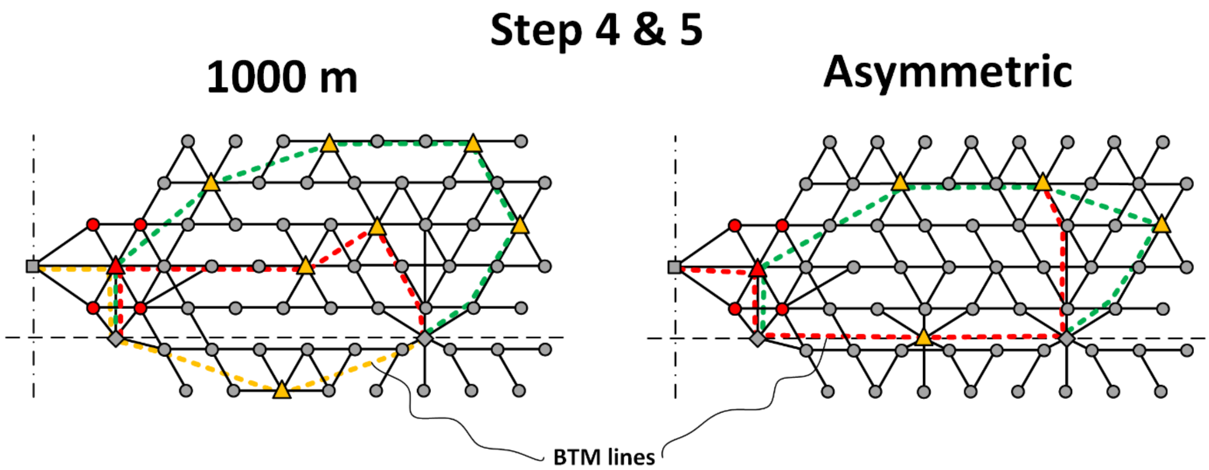


Figure 42 Step 4 & 5 with left 1000 m alternative and right the Asymmetric alternative

Calculation Results

With the multimodal network designs for both alternatives, the total (experienced) travel times and (experienced) connection qualities for each residential node can be calculated. As stated earlier, the travellers travel mainly to the commercial nodes, or to a train station (no preference). Therefore, two types of calculations were made. First, the calculations for trips to the middle commercial node were made. Secondly the trips to the train stations were calculated.

In Table 37, the overall results of both alternatives are shown. In the table, the 1000 m alternative is used as reference point. In the Figures 43 & 48, the total travel times, mode choices, and connection quality results (both regular and experience factor) for each residential node are shown. According to Table 37, the Asymmetric alternatives score only a bit better. When looking to the trips to the commercial node, the aggregated total travel times are more or less the same. Also the number of nodes with a faster or slower total travel time is almost equal. With the total experienced travel time, the differences become a bit larger. Furthermore, the number of nodes with a faster experienced travel time has increased, while the amount with a slower experienced travel time has decreased. For trips to the train stations, a similar pattern can be found.

Table 37 Total (experienced) travel time results compared to 1000 m alternative

	Total Travel time				**Total Experienced Travel time**			
	TT (min)	delta (%)	# Nodes Faster	# Nodes Slower	TT (min)	delta (%)	# Nodes Faster	# Nodes Slower
To Commercial Node								
1000 m	1502	-	-	-	1601	-	-	-
Asymmetric	1500	0,1	13	12	1580	1,3	14	9
To Train Station								
1000 m	876	-	-	-	-	-	-	-
Asymmetric	869	1	10	7	799	3	9	5

In the figures 43 & 44, the mode choices of each residential node are shown. Figure 43 is for trips to the middle commercial node and Figure 44 to the train stations. For trips to the commercial node, the possible mode choices were: bicycle-only, E-bike-only (if too far for regular bicycle), bicycle+BTM+ walking, bicycle+train+shared-bike, and bicycle+BTM+Train+shared-bike. All residential nodes within the bicycle door-to-door catchment area have the bicycle-only trip as fastest mode choice. Even if the node also has a BTM stop, cycling directly to the destination is faster. Also the E-bike is, when possible, often chosen. Only if the node itself has a BTM stop, a multimodal trip was more attractive. When using the experienced travel times, the E-bike is always more attractive.

Also the mode combination bicycle+train+shared-bike is often chosen in both alternatives. Even if a BTM stop is closely located, it is for several residential nodes faster to travel more than 1 km upstream to a train station. The mode combination bicycle+BTM+train+shared-bike, is a lot less popular. Only with the experienced travel time in the 1000 m alternative, this combination is attractive for some nodes.

For trips to the train stations, a similar pattern is found. If close enough, the bicycle-only trips are always faster than a multimodal trip. The E-bike is only slower when the residential node also has a BTM stop, and the BTM route goes without detours to the station.

According to the mode choice results, the bicycle-only trips are always the most attractive mode choice for destinations and train stations within the bicycle catchment area. Therefore, placing BTM stops within these catchment areas is less effective to apply. In the 1000 m alternative, this occurs for two BTM stops. It does not occur in the asymmetric alternative. Based on these observations, it can be said that the BTM nodes in the Asymmetric alternative are used more effective. For trips to a train station, the same pattern applies.

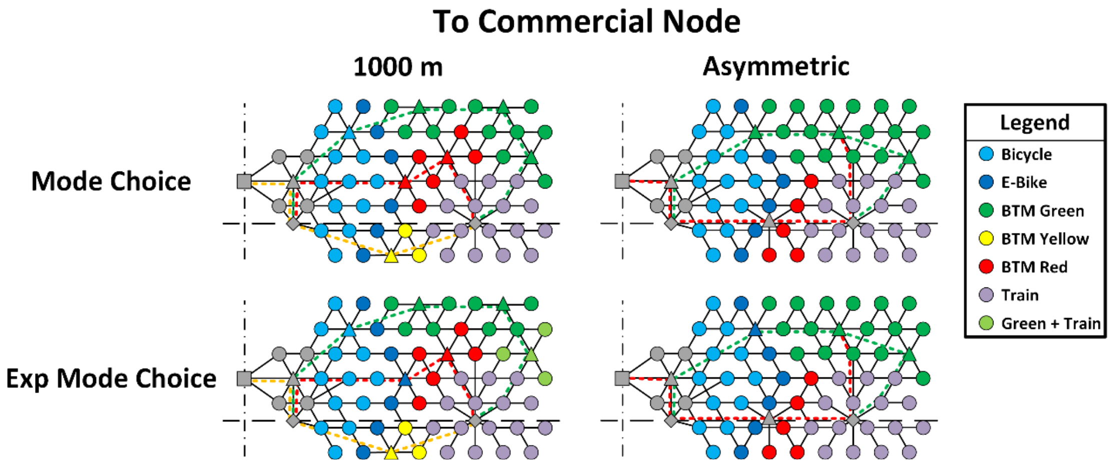


Figure 43 Mode choice per node for trip to commercial node

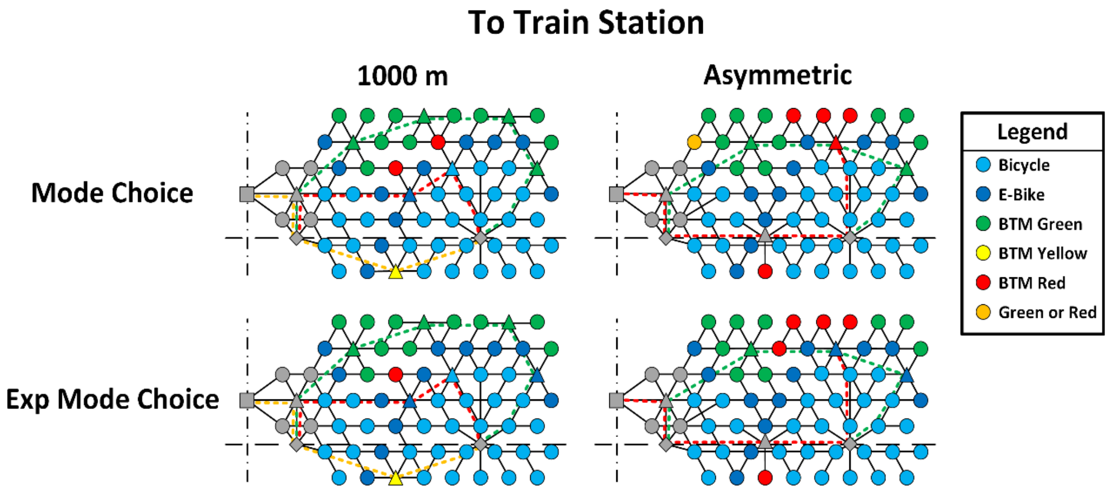


Figure 44 Mode choice per node for trip to train station

In the Figures 45 & 46, the total (experienced) travel time per residential node for both trips is shown. In Figure 45, the results for trips to the commercial nodes are shown. As you can expect, the residential nodes located close to the commercial nodes have a lower total (experienced) travel time than the residential nodes located further away. An exception is the area around the train station, where the travel times are relative low as well.

Between the two alternatives, several differences can be observed. In the 1000 m alternative, three nodes have a total travel time of more than 40 minutes (Red) while the Asymmetric only has one. However, the Asymmetric has more nodes with a travel time above the 30 minutes. These results indicate that the Asymmetric alternative is more effective in preventing very high travel times at the expense of fewer nodes with a relative low travel time. A similar pattern can be found with the experienced travel time. The 1000 m alternative has more nodes with an experienced travel time above the 45 minutes, but an equal amount of nodes with more than 35 minutes compared to the Asymmetric.

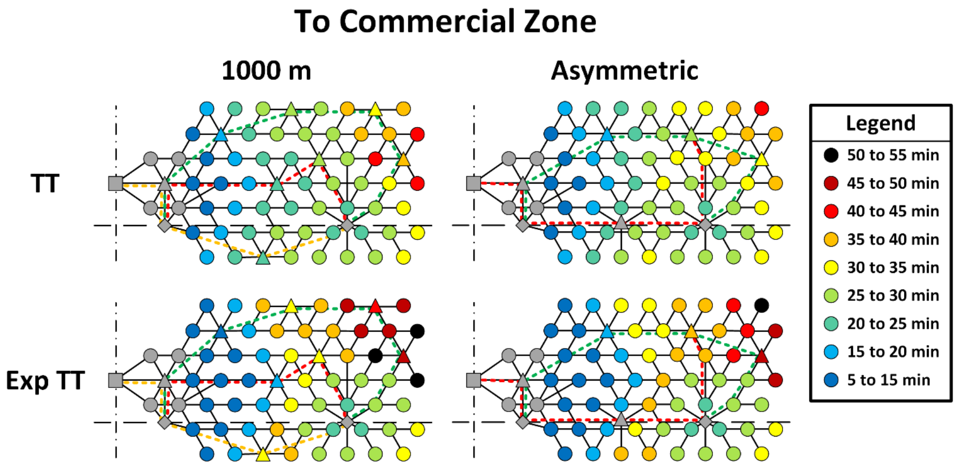


Figure 45 Heatmap total (experienced) travel time for trips to commerical node

For trips to the train station, the Asymmetric alternative is more advantageous. The 1000 m alternative has more nodes with a travel time above the 25 minutes and 20 minutes, compared to the Asymmetric. The same applies when using the experienced travel times.
Overall, the total (experienced) travel time results indicate that the Asymmetric alternative does not create a large travel time decrease for the whole area. But, the 1000 m alternative has a higher fluctuations of travel time values, while the Asymmetric is more homogeneous. Furthermore, the Asymmetric is more suitable for nodes located further away from the destination node.

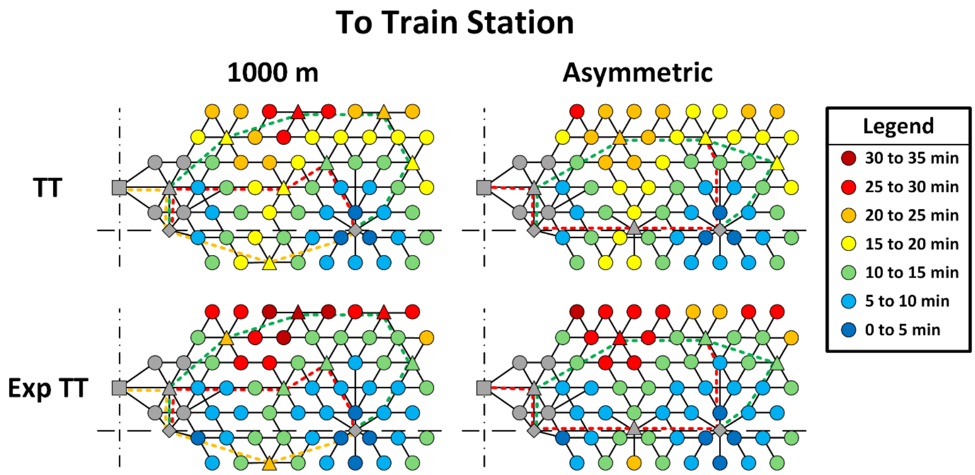


Figure 46 Heatmap total (experienced) travel time for trips to train station

The (experienced) connection quality results are shown in the Figures 47 & 48. Figure 47 shows the results for trips to the commercial node. With regular travel times, nodes located further away often have a higher connection quality than the residential nodes with bicycle/E-bike only as mode choice. Especially the nodes with the bicycle+train+shared-bike as mode choice have a high connection quality. Only the nodes located just too far away for an E-bike only trip may have a poor connection quality. With the experienced travel times, more residential nodes gained a poor experienced connection quality score.
Also with regard to the connections quality, some differences between the alternatives are noticeable. In the right-above corner of the area, it can be seen that the values with the Asymmetric alternative are more homogeneous than in the 1000 m alternative. For the residential nodes in the middle of the area, the 1000 m alternative is more suitable. With the experienced travel time, a similar pattern can be found.

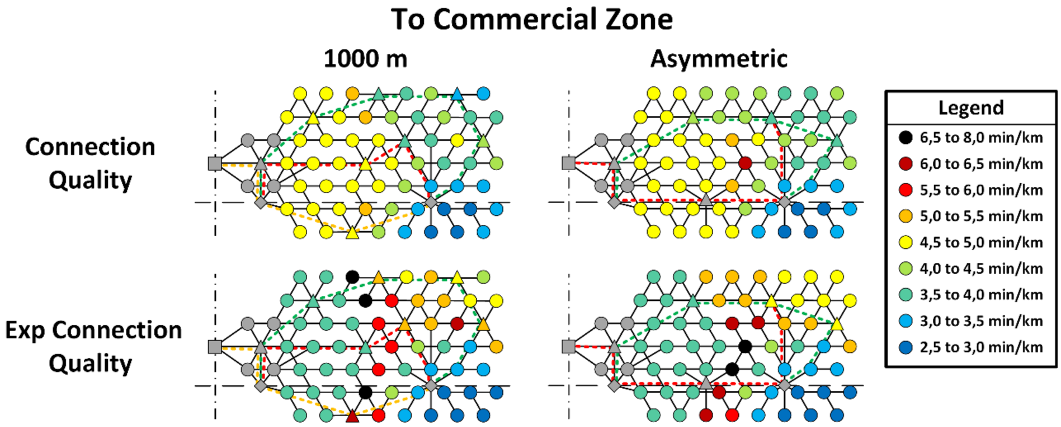


Figure 47 Heatmap (experienced) connection quality for trips to commercial node

For many nodes, the bicycle/E-bike only was the most attractive mode choice for trips to a train station. As consequence, most of these nodes have the same min/km value. Therefore, the differences between the two alternatives are limited. Still, some differences can be found. According to the connection quality values, the Asymmetric alternative has one node more with a value higher than 5,5 min/km. but, it also has more nodes with a value lower than 4,5 min/km. With the experienced connection quality, the pattern changes a bit. In this case, the 1000 m alternative also has more nodes with a value higher than 6,0 min/km compared to Asymmetric.

Overall, The (experienced) connection quality results show that the differences between the alternatives are small. But it seems that the Asymmetric in most cases create less poor (experienced) connection quality results.

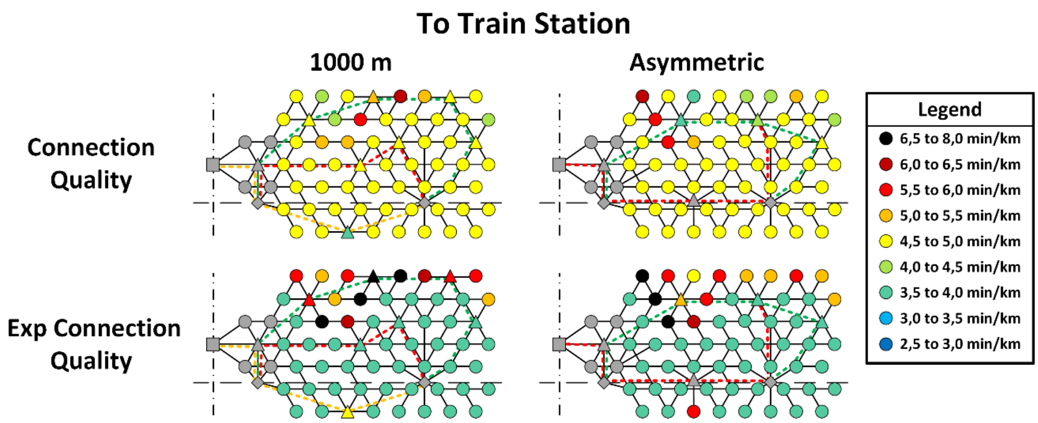


Figure 48 Heatmap (experienced) connection quality for trips to train station

Sensitivity Results

Like in the previous two scenarios, a sensitivity analysis is done. Again, the operational speed values of the BTM and cycling are changed. In the Tables 38 & 39, the sensitivities of the total travel time results are shown. The Tables 40 & 41 show the results with the experienced travel time.

According to Table 38, increasing the BTM speed has a more positive impact for the 1000 m alternative. For trips to the commercial node, this alternative scores even better than the Asymmetric. It also influences the number of nodes with a faster or slower travel time, shown in Table 39. While the Asymmetric first had more nodes with a faster travel time, increasing the BTM speed flips it to more with a slower travel time. For trips to the train stations, the Asymmetric is still slightly better in both total travel time and number of nodes with a faster/slower travel time. Increasing the cycling speed is more favourable for the Asymmetric alternative.

Table 38 Difference in total travel time between 1000 m and Asymmetric alternative with different speed values

	Default		BTM 30 km/h		BTM 40 km/h		Cycling 15 km/h	
	∑TT (min)	ΔTT (%)	∑TT (min)	ΔTT (%)	∑TT (min)	ΔTT (%)	∑TT (min)	ΔTT (%)
To Commercial Node								
1000 m	1502	-	1435	-	1348	-	1381	-
Asymmetric	1500	0.1	1445	-0.7	1369	-1.5	1368	0.9
To Train Station								
1000 m	875	-	841	-	816	-	776	-
Asymmetric	867	0.9	837	0.5	795	0.3	764	1.6

Table 39 Number of nodes having a faster or slower travel time compared to 1000 m alternative with different speed values

	Default		BTM 30 km/h		BTM 40 km/h		Cycling 15 km/h	
	∑TT (min)	ΔTT (%)	∑TT (min)	ΔTT (%)	∑TT (min)	ΔTT (%)	∑TT (min)	ΔTT (%)
To Commercial Node								
1000 m	-	-	-	-	-	-	-	-
Asymmetric	13	12	11	16	15	18	12	11
To Train Station								
1000 m	-	-	-	-	-	-	-	-
Asymmetric	10	7	12	11	12	11	8	6

Also with the experienced travel time (Tables 40 & 41), the difference between the two alternatives has become smaller when increasing the BTM operational speed. Unlike with the regular travel time, the Asymmetric alternative is still scoring, slightly, better for trips to the commercial node.

According to the sensitivity analysis results, the (experienced) travel time differences stay relative small when changing the BTM- and cycling speed. Increasing the BTM speed makes the difference even smaller. Still, the Asymmetric alternative scores in most cases slightly better than the 1000 m alternative.

Table 40 Difference in total experienced travel time between 1000 m and Asymmetric alternative with different speed values

	Default		BTM 30 km/h		BTM 40 km/h		Cycling 15 km/h	
	∑TT (min)	ΔTT (%)	∑TT (min)	ΔTT (%)	∑TT (min)	ΔTT (%)	∑TT (min)	ΔTT (%)
To Commercial Node								
1000 m	1601	-	1529	-	1436	-	1506	-
Asymmetric	1580	1.3	1515	0.9	1434	0.2	1483	1.6
To Train Station								
1000 m	821	-	785	-	740	-	746	-
Asymmetric	798	2.9	769	2.1	733	0.9	718	3.8

Table 41 Number of nodes having a faster or slower travel time compared to 1000 m alternative with different speed values

	Default		BTM 30 km/h		BTM 40 km/h		Cycling 15 km/h	
	∑TT (min)	ΔTT (%)	∑TT (min)	ΔTT (%)	∑TT (min)	ΔTT (%)	∑TT (min)	ΔTT (%)
To Commercial Node								
1000 m	-	-	-	-	-	-	-	-
Asymmetric	14	9	12	11	12	11	14	9
To Train Station								
1000 m	-	-	-	-	-	-	-	-
Asymmetric	9	5	8	6	8	6	9	5

Costs
For both alternatives, a simple cost indication is calculated based on the values in Table 20. In Table 42, the costs are shown for the categories construction of infrastructure (road/track + BTM stop), maintenance of infrastructure, and vehicle costs. For each cost category, the costs are shown when applying the bus, tram or metro (50/50 above- and underground).
Unlike with the previous results, the difference between the alternatives have become much larger. It appeared that the Asymmetric alternative is much cheaper to apply. Dependant of the transit type, the savings can be millions of euro's. Main reason of this difference is the need of an extra BTM service line in the 1000 m alternative. The table also shows the high cost difference between the three transit modes. Especially applying the metro can be very expensive.

Table 42 Costs per alternative in millions of euros

	Infrastructure			**Maintenance**			**Vehicles**		
Alternative	Bus	Tram	Metro	Bus	Tram	Metro	Bus	Tram	Metro
1000 m	68	326	2258	2.7	16	27	5.4	27	36
Asymmetric	53	256	1777	2.2	13	22	3.6	18	24

Conclusion Mobili-City
In the Mobili-City scenario, the first multimodal networks with the bicycle as core were made. This was done by using the information and results from the literature study and the first two scenarios. Also the design strategy was implemented, after some adaptions. For the Mobili-City scenario, two alternatives called "1000 m" and "Asymmetric" were made. In the first alternative, a bicycle catchment radius of 1000 m for BTM stops was applied. The second alternative uses an asymmetric catchment area (1000-2000 m). With the results from the calculations, the first answers for the sub-question "*Which applications of multimodal networks with the bike as core are suitable to implement in a network*" can be given. Furthermore, a first conclusion about the effectiveness of the design strategy as a tool can be made.
Before designing the alternatives, some changes in the design strategy were needed. Based on the results from the first two scenarios, an asymmetric (1500-2500 m) catchment area for train stations is more suitable when the train trip is relative short. Furthermore, when asymmetric catchment areas are applied, the location of the destination should be taken into account.
During the design of the alternatives, it appeared that for the 1000 m more BTM stop and service lines were needed. As consequence, this alternative has become much more expensive than the Asymmetric alternative.
With the final designs, the total (experienced) travel times, mode choices, and (experienced) connection qualities for each residential node were calculated. The main travel destinations were the commercial node and train stations. The mode choice results showed that if the residential node is within the catchment area of the destination, a door-to-door bicycle trip is always more attractive than other mode options. Even if the residential node itself has a BTM stop, the bicycle only trips is still more suitable. When the destination is too far for a bicycle trip but in range for E-bike, the E-bike is often the fastest option. Only if a BTM stop is in the node itself, the bicycle+BTM can be more attractive. These results indicate that the used catchment radius values for the door-to-door bicycle/E-bike trips seems suitable. This also accounts for the trips to a train station.
The (experienced) travel time and (experienced) connection quality showed mainly small differences between the alternatives. One of the main observations was that the Asymmetric alternative created less extreme high (experienced) travel times and (experienced) connection qualities. Also in the sensitivity analysis, the differences are small.
Eventually, it seems that the Asymmetric alternative seems the best option. While the differences in travel times and connection quality are very small, applying an asymmetric catchment radius creates a much cheaper transit network.

3.4 CONCLUSION

The sub-questions in this chapter were:
"What are the effects of the combined bicycle catchment radius and (multilevel) transit services on the travel time and accessibility?"
"Which applications of multimodal networks with the bicycle as core are suitable to implement in a network".

In this chapter, the main goal was to find out how to apply and design a multimodal network with the bicycle as core. In the literature study, a lot of information about catchment radius of bicycles, trip preferences of travellers, and multimodal network & -service outlines were obtained. After the literature study, some information was still missing. It was still unknown how combinations of a bicycle catchment radius and a (multilevel) BTM service affect the total (experienced) travel time and (experienced) connection quality. Therefore the bicycle-transit combinations was first studied. To do this, two scenarios called "Corridor" and "2D Corridor" were made. The main goal of these scenarios was to study the effects of bicycle catchment radius and (multilevel) transit service combinations on the total (experienced) travel time and (experienced) connection quality. After finishing these two scenarios, the first designs of multimodal networks with the bicycle as core are made in a third scenario called "Mobili-City".

The Corridor scenario consisted of one long 1 dimensional corridor, with every 300 m a node. In this scenario, different combinations of bicycle catchment radius and BTM services were combined. With the results, the different combinations were compared. Also a comparison with the walking alternatives were made, to see if a bicycle-BTM mode combination is indeed faster than the walking-BTM equivalent. The results showed that the bicycle-BTM combination is in general faster than walking-BTM. This confirms the potential of combining the bicycle and transit modes in multimodal transport. After comparing the results of the different bicycle-BTM combinations, several conclusions could be made. An observation was the negative impact of travelling first "upstream" to a BTM stop while the destination is located downstream. This was most notable when using a bicycle catchment radius of 2000 m. Only if the travel distance is quite long (more than 20 km), the negative impact can be seen as small. Meanwhile, applying a 2000 m radius was profitable for travellers travelling downstream to a BTM stop. Eventually, the asymmetric catchment area (1000-2000 m) created, on average, a lower total (experienced) travel time compared to the circular catchment areas. Furthermore, the (experienced) travel times and (experienced) connection qualities were less fluctuating. Combined with a traditional BTM service (stops at every stop), it could compete with the alternatives having a multilevel service. When using the experience factor, it even scored much better than all other combinations. Only the zone-based BTM service approach improved the total (experienced) travel time and (experienced) connection quality more. In the zone-based approach, a bicycle catchment radius of 1000 m for low level stops and 2000 m for high level stops were used. However, a zone-based approach is only useful if there are many stops in a corridor, and these stops are not located in high demand zones.
Downside of the "Corridor" was the use of an 1D line, instead of a 2D plane. For re-examine the effects of a bicycle catchment radius on the travel times and connection qualities, the second scenario called "2D corridor" was mode. In this scenario, the effects of applying a 1000 m, 2000 m, or an asymmetric bicycle catchment radius in a 2D plane were studied. Overall, the results showed that the conclusions made in the first scenario still holds. However, the differences between applying a 1000 m and an asymmetric catchment radius has become smaller. Therefore, it can be said with less certainty that applying an asymmetric catchment area is better than the circular 1000 m radius for BTM stops.

In sub-chapter 3.2, the design strategy was described. Based on the results of the first two scenarios, some adjustments are needed. In the description of the strategy, circular catchment areas were assumed. When applying asymmetric catchment areas, the location of the destination becomes

important. if there are multiple main destinations, each node will need multiple catchment areas, depending on the destination.
Due to the negative score of the 2000 m catchment radius for BTM stops, the question rises if the current catchment area of the train stations (2500 m) is too high. Eventually, it seemed more suitable to use an asymmetric bicycle catchment area (1500-2500 m) for train stations when the train trips are short.

In the Mobili-City scenario, the first multimodal networks with the bicycle as core were designed. Based on the information and results from the literature study, first two scenarios and the adapted design strategy, two alternatives were designed. The first alternative used a bicycle catchment radius of 1000 m for BTM stops, and the second an asymmetric (1000-2000 m). The results showed that in terms of total (experienced) travel time and (experienced) travel quality, the difference between the two alternatives were small. In most occasions, the Asymmetric scored slightly better. Furthermore, the Asymmetric had often less extreme high values, and it was more favourable for nodes located further away of their destination. But, the difference became much larger when looking to the costs. It appeared that creating a multimodal network with asymmetric catchment areas has much lower costs than using a 1000 m radius. Therefore, using an asymmetric catchment area for BTM stops seems much more effective.
The mode choice results could be used to examine the bicycle catchment radius of both the door-to-door trips and the train stations. It appeared that for nodes within these catchment areas, a direct bicycle trip was always faster, even if a BTM stop was located nearby. For the nodes too far located for bicycle only trips, but within the catchment area of the E-bike, the E-bike was often faster as well. Only if the node itself had a BTM stop, combining the trip with a BTM was faster. These results indicate that the used catchment radius in the design strategy reflect, the range in which a door-to-door trip or direct cycling trips to a train station is often faster. Originally, these ranges were mostly based on the travel distance willingness. However, this changes when the BTM operational speed increases.

The last sub-question of this thesis was: "*Which applications of multimodal networks with the bicycle as core are suitable to implement in a network*". With the results of this chapter, a first answer can be given. According to the results, the bicycle catchment area for BTM stops should be asymmetric (1000-2000 m) and dependant on the location of the destination. For train stations, an asymmetric bicycle catchment area (1500-2500 m) also more suitable when the train trip is short. The radius values for door-to-door bicycle trips and trips to train stations (long train trip) determined in the literature study do not only reflect the maximum travel distance willingness on a bicycle and E-bike, but also the range in which the bicycle and E-bike is often faster. This chapter also showed that for an effective bicycle-BTM combination, a traditional or a zone-based BTM service approach should be used. Applying these values and measures should create a multimodal network, which is attractive for travellers to use.

4 CASE STUDY

The three scenarios examined in the Theoretical Application chapter showed that a bicycle-transit combination decreased the (experienced) travel time for the traveller compared to a walk-transit combination. Furthermore, the results indicated that an asymmetric catchment area for BTM stops combined with a traditional BTM service outline is the most suitable combination to use in a multimodal network with the bicycle as core. This information will be used in this case study, to answer the last sub-question and the main question. These questions are:

Sub-question: *"To what extent is it possible to decrease car-use by applying a multimodal network with the bicycle as core"*

Main question: "*To what extent does a multimodal passenger transport network with the bicycle as core reduce the total travel time for most travellers and increase the modal split for (multimodal) transit trips, without high investment- and operational cost"*

Like in the 'Mobili-City' scenario, a multimodal network with the bicycle as core is designed for the case study area called 'Utrecht Science Park'[VI] (USP). This science park consists of a large university, a school for applied sciences, an academic hospital and many companies. On a daily base, it attracts ten thousands of students, employees and visitors. Most of these travellers live outside the USP area. In the near future, the government of both the city and Utrecht province expects overcrowding of Utrecht Central Station (CS) and the new Uithoflijn (tram line from Utrecht CS to USP) (Intern information, no official source). To solve these issues, The government is studying the possibilities of constructing feeder stations around the city (U Ned, 2018).
In this case study, the transport model called "Vervoers Regio Utrecht" (VRU) is used. This model runs on Omnitrans, which is a trip-based static simulation software based on the 4-step model[VII]. With the VRU model, trips within the province of Utrecht can be simulated. This makes it possible to determine the modal split and intensities at transit trajectories, -stops and -stations. The modal split can be used to determine the decrease of car-use and increase of (multimodal) transit trips. The intensity values are useful to study the attractiveness of transit routes, and the number of cyclists from and to a transit stop, -station, and P+R.

The main goal of this case study is to design a multimodal network with the bicycle as core for the area around the USP see sub-chapter 4.1. However, it may be possible to combine this goal with the aim of the local authorities to unburden Utrecht CS and the Uithoflijn. For this case study, two alternatives will be created plus a zero alternative. The first one is the basic alternative, which focuses primarily on the main goals of this case study and thesis. In the "Plus" alternative several small changes in the design of the basic alternative are made to create feeder stations. With these feeder stations, Utrecht central station and The Uithoflijn might be relieved.
A more extended description of the case study is given in the next sub-chapters:

In 4.1, a more detailed description of this case study is given. 4.2 shows the design process of both alternatives. 4.3 describes the limitations of the VRU model and how these limitations are -if possible- handled or solved. This sub-chapter also describes the implementation of the alternatives into the model. In 4.4, the simulation results, are described. Based on the results a conclusion for the case study is drawn in sub-chapter 4.5. In 0, Several suggestions for the Province of Utrecht and its municipalities are presented.

[VI] Formerly known as De Uithof
[VII] Trip Generation => Trip Distribution => Mode choice => Route Assignment

4.1 CASE STUDY DESCRIPTION

In Figure 49, the region around the Utrecht Science Park is shown. It is a divers region with different types of land use and urbanisation. The USP is located at the eastern side of Utrecht between the highways A27 and A28. While the west side of the A27 is mostly an urbanised area, the east side is much more a mix of small cities, farmland and forests. As Utrecht CS is the main train node in the Dutch train network, several train tracks and -stations are located in the area. Furthermore, the extended tram tracks to the USP will be opened in the second half of 2019. This tram line finishes at the P+R of the USP. This is the only P+R not located next to a train station.
In the case study, only the area at the east side of the A27 during the network design is considered. Exceptions are the train station Lunetten and the tram tracks between Utrecht CS and USP. Utrecht itself is excluded as this city already has the Uithoflijn as connection to the USP and four train stations. Therefore, including Utrecht seems not necessary.

For this case study, the formulated main- and sub-goals in Chapter 1.1.1 are applicable numerated below:

"Design and study the effects of a multimodal network with the bicycle as core on the attractiveness of multimodal passenger transport in terms of travel time, transit-use and operational costs"

Sub-goals

- Optimize the use and routes of the bicycle
- Improve bicycle-transit combination use
- Decrease car-use

In the theoretical scenarios, land use and surroundings were disregarded. Despite these subjects are not an important part of this thesis, they should not be disregarded in this case study. Therefore, when introducing new infrastructure, stops, stations and/or transit lines, the feasibility in terms of available space, and surrounding area need to be taken into account. For example, placing a BTM stop in the middle of a neighbourhood with only small roads is not considered feasible. Furthermore, new infrastructure is only introduced when existing infrastructure is absent or not adequate. If new infrastructure is introduced, it should be tried to bundle this with other infrastructure types to limit the extra hinder. For instance, designing a BTM road right next to a highway or train tracks.
In the case study area, several locations are considered as protected area (red area). In this area, it will not be possible to introduce new non-bicycle infrastructure nor to design transit routes through it. So, between the USP and Bunnik, a direct transit corridor is not possible. Between USP and Zeist, only a transit corridor right next to the A28 is feasible. The dark green area is part of the Utrechtse Heuvelrug which is a large forest (and even has some hills). Constructing new infrastructure through this forest is also unfeasible, unless bundled with other infrastructure.

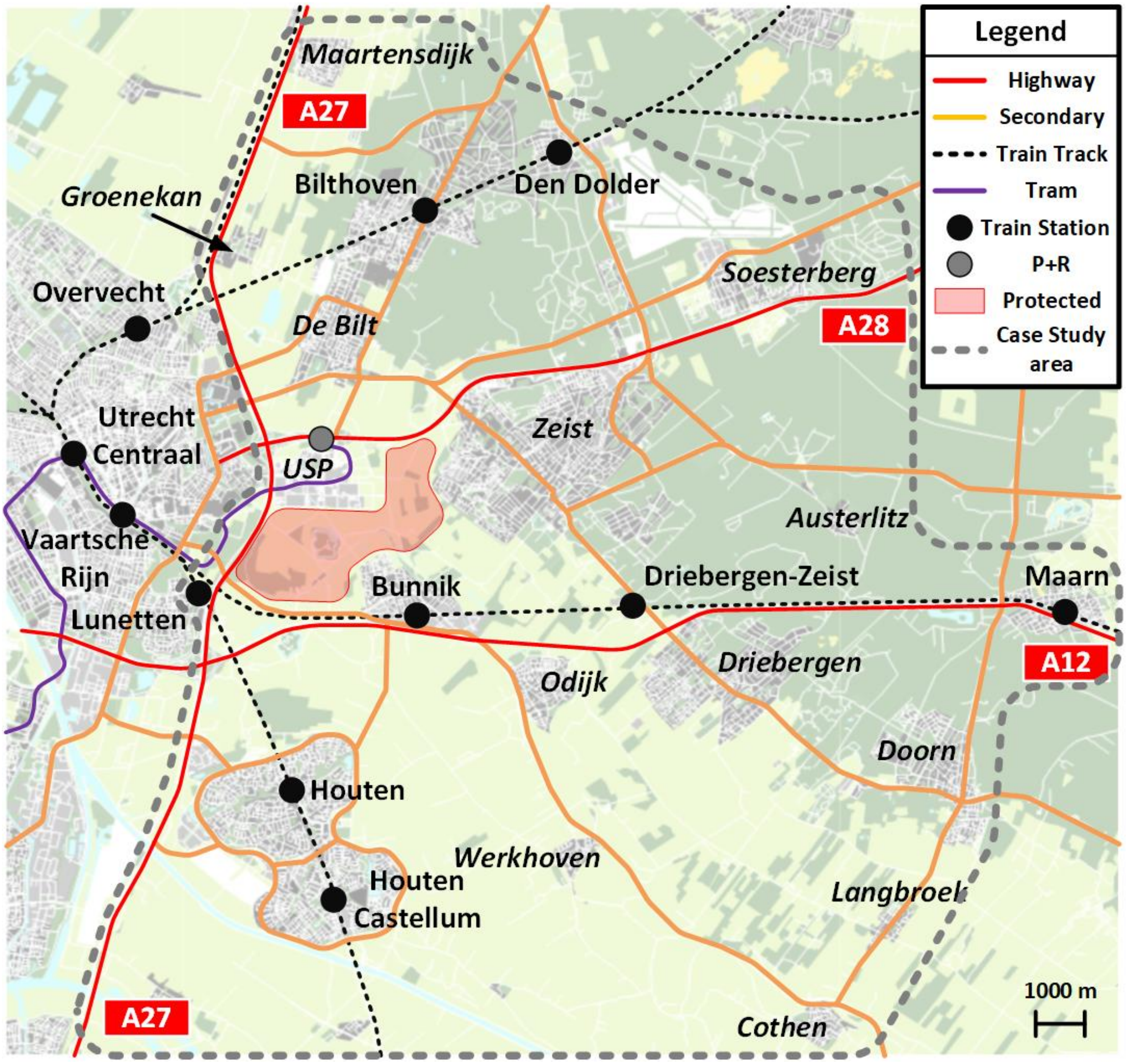


Figure 49 Case Study area

4.2 Design Multimodal Network

To design a multimodal network with the bicycle as core for the USP area, the design strategy discussed in sub-chapter 0 and 3.3.3 will be re-used. One large difference is that the VRU model works with hundreds of small zones. As it is difficult to visualise all these zones, the zones will not be shown in the figures.

Step 1

The first step is to design bicycle routes to the USP for zones within the door-to-door catchment area of the bicycle or E-bike. The results are shown in Figure 50. As the USP is relative large, catchment areas at each corner are drawn. Within these catchment areas, bicycle routes to the USP are drawn. For visualization reasons, only the main bicycle path corridors are shown. At the moment, only a part of the corridor between the USP and Zeist does not exist (shown in blue dots). Adding this path will save distance up to 1,5 km for cyclists. For the other paths no direct measures are needed. However, to make cycling more attractive, specific measures like giving priority, broader cycling paths, and priority at traffic lights could be taken. This will make door-to-door cycling trips to the USP more attractive. For zones outside the bicycle catchment area, a bicycle-transit combination is needed for trips to the USP.

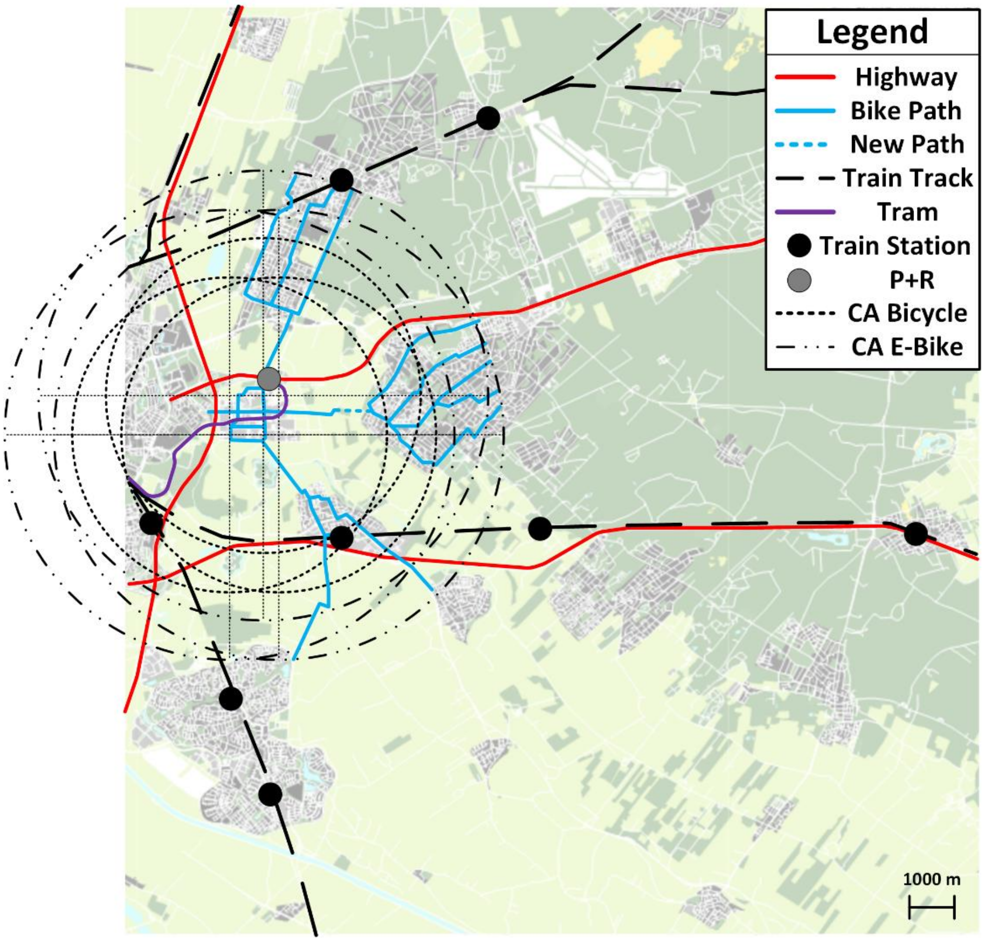


Figure 50 Step: 1 Design of Door-To-Door routes to USP

Step 2

With the completion of drawing bicycle routes to the USP, the same can be done for cycling to the train stations. In Figure 51, the bicycle, E-bike and shared-bike catchment areas for each train station within the region are drawn. Furthermore, the catchment area of the shared-bike for the P+R is drawn. Like in the first step, bicycle routes to the stations are drawn for the zones within these catchment areas. The shared-bike catchment areas are used to identify if an egress shared-bike trip from the station or P+R to the USP is feasible.

The figure indicates that only the P+R is located close enough to the USP for egress shared-bike trips. All train stations are too far away for egress shared-bike trips to the USP. Therefore, BTM connections between the train stations and the USP are needed for train users. After implementing the bicycle routes, one new bicycle path is added between the cities Bunnik and Zeist. The rest consist of existing bicycle paths. It is noticeable that Houten[VIII] is fully covered by the bicycle catchment areas of two stations. Most of the city is even in range for shared-bike egress trips. As travellers in this city can easily access the train station, a BTM transit line is not needed. For many other cities and areas, a BTM connection to a train station is needed.

[VIII] Houten is a good example of transit oriented development

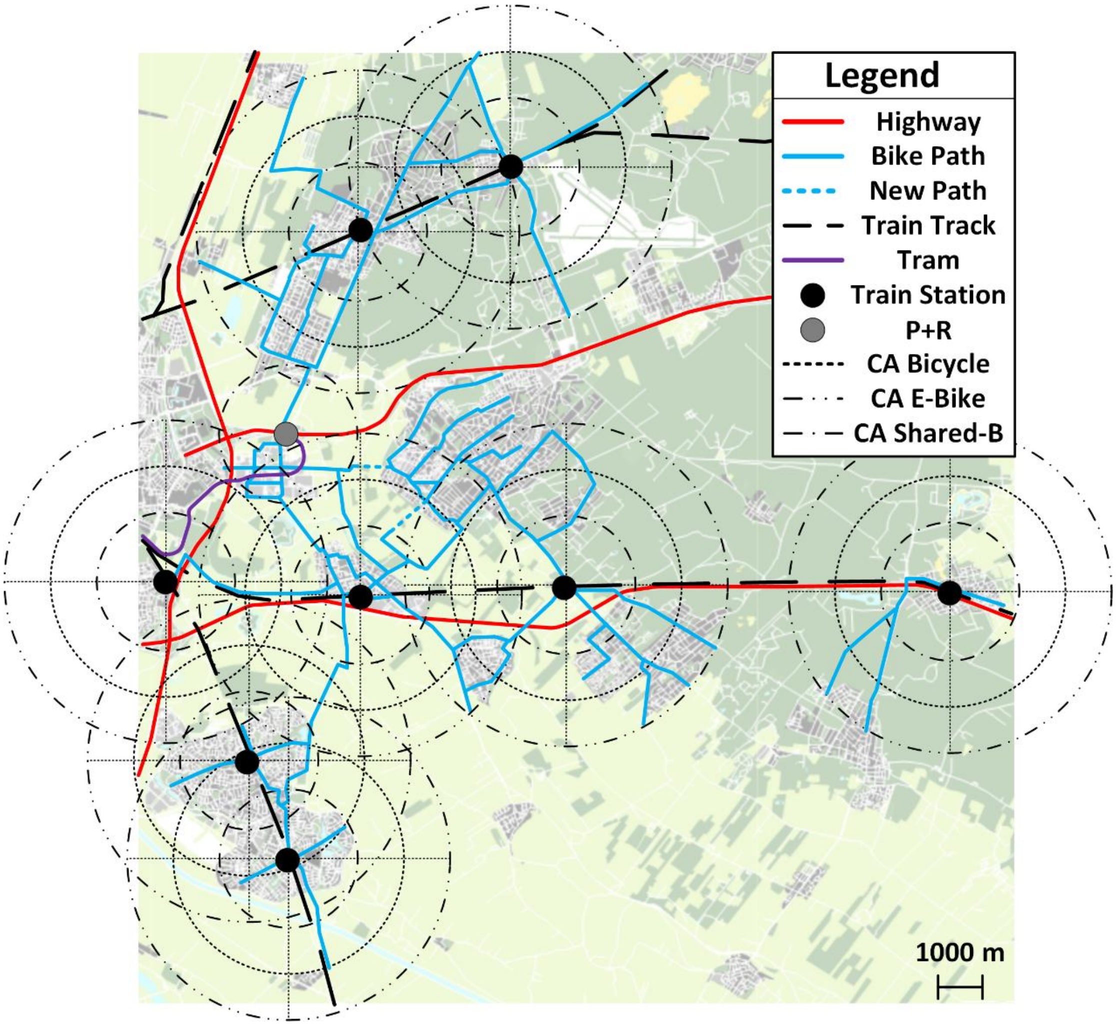


Figure 51 Step 2: Design of Bicycle routes to existing train stations

Step 3

As it has become clear which zones are in need of a BTM connection, locations for new BTM stops and, if feasible, new train stations are determined. In Figure 52, step 3 is visualised. For the train stations, three different types of bicycle catchment areas are drawn. The circular area (2500 m) represents the range of cycling access trips to the train station for long train trips. The largest asymmetric area (1500-2500 m) is for trips to the USP with the train as transit mode. The smaller asymmetric area (1000-2000 m) is also for trips to the USP, but the traveller transfers to a BTM instead of train. As stated in the previous chapter, the shape of an asymmetric catchment area is dependent of the location of the destination zone. In this case study, the primary destinations are the USP and a train station (for travelling out of the case study area). For the BTM stops, it means that the bicycle catchment area is variable. In Figure 52, the bicycle catchment areas are set for the USP as destination. For visual reasons, catchment areas for travelling to the train stations is not shown in the figure.

Eventually 12 BTM stops (yellow) and 2 train stations (Red) are added. One train station is added next to Maartensdijk and the other between the cities Driebergen and Austerlitz. By placing these two stations, Maartensdijk and Austerlitz can cycle directly to a train station instead of needing an extra BTM link. This saves an extra transfer. As Austerlitz lies quite isolated, it also reduces the complexity when designing the BTM lines. At both train stations, only the stop train (Sprinter) will stop.

With these locations for BTM stops, the urbanised areas in need of a BTM connection are now within the catchment area of at least one BTM stop. While not preferred, it was in some occasions not possible to prevent large overlap of catchment areas from different stations or stops. While not in an urbanised area, the BTM stop "Soesterberg, Kazerne" is added due to the presence of a large military base and other (semi-)military activities. This is also the only stop that does not has a catchment area orientation on the USP as destination, as this base is mostly a receiver of travellers. Instead, the catchment area is focussed on train station Den Dolder.

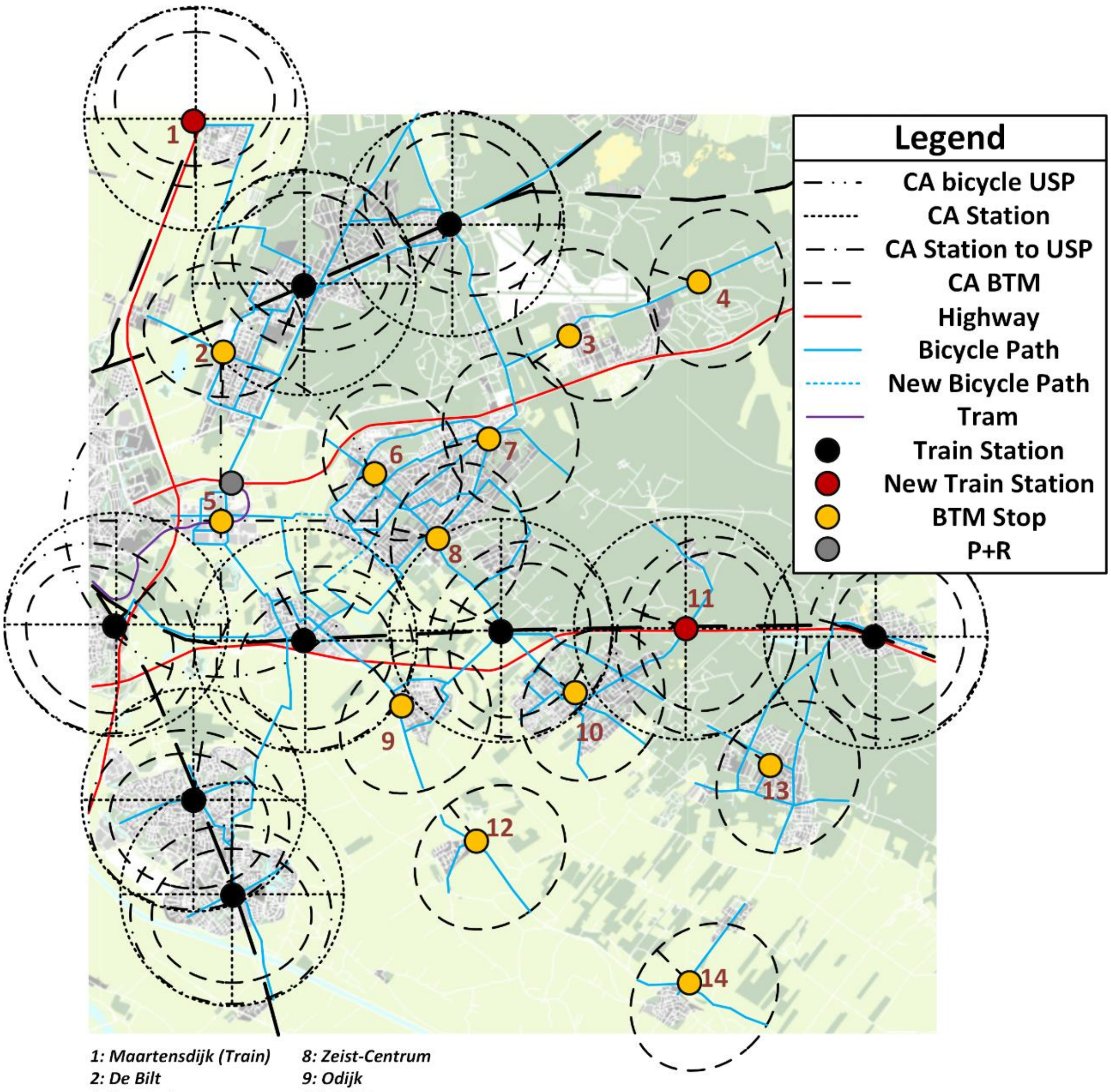


Figure 52 Step 3: Final locations of BTM stops and extra train stations

Step 4

Having the final locations for the new BTM stops and train stations, the BTM lines can now be implemented. The main task of these lines is to create BTM connections to the USP and to a train station for the travellers. So, every BTM stop should have a direct BTM line to the USP and at least one train station. During the design of the routes, it is preferred to limit the number of transit lines and detours. The final results are shown in Figure 53. Eventually, 5 new BTM lines are added into the network. Furthermore, the existing tram line (purple) is extended to Den Dolder through Bilthoven. For a part of this extended route, the existing train tracks can be used. For the other lines, multiple different BTM modes are possible. While outside the case study area, The BTM lines blue and yellow start at Utrecht CS and also stop at train station Vaartsche Rijn. The BTM lines red, dark red, and yellow ends outside

the case study area. Overall, all BTM lines and train tracks combined create a ring-radial transit network with Utrecht CS in central position.
With these BTM service line setup, train travellers can transfer at Maartensdijk, Bilthoven, Bunnik, or Lunetten to a BTM line with a direct connection to the USP. Furthermore, every BTM stop has a direct connection to the USP and at least one train station.

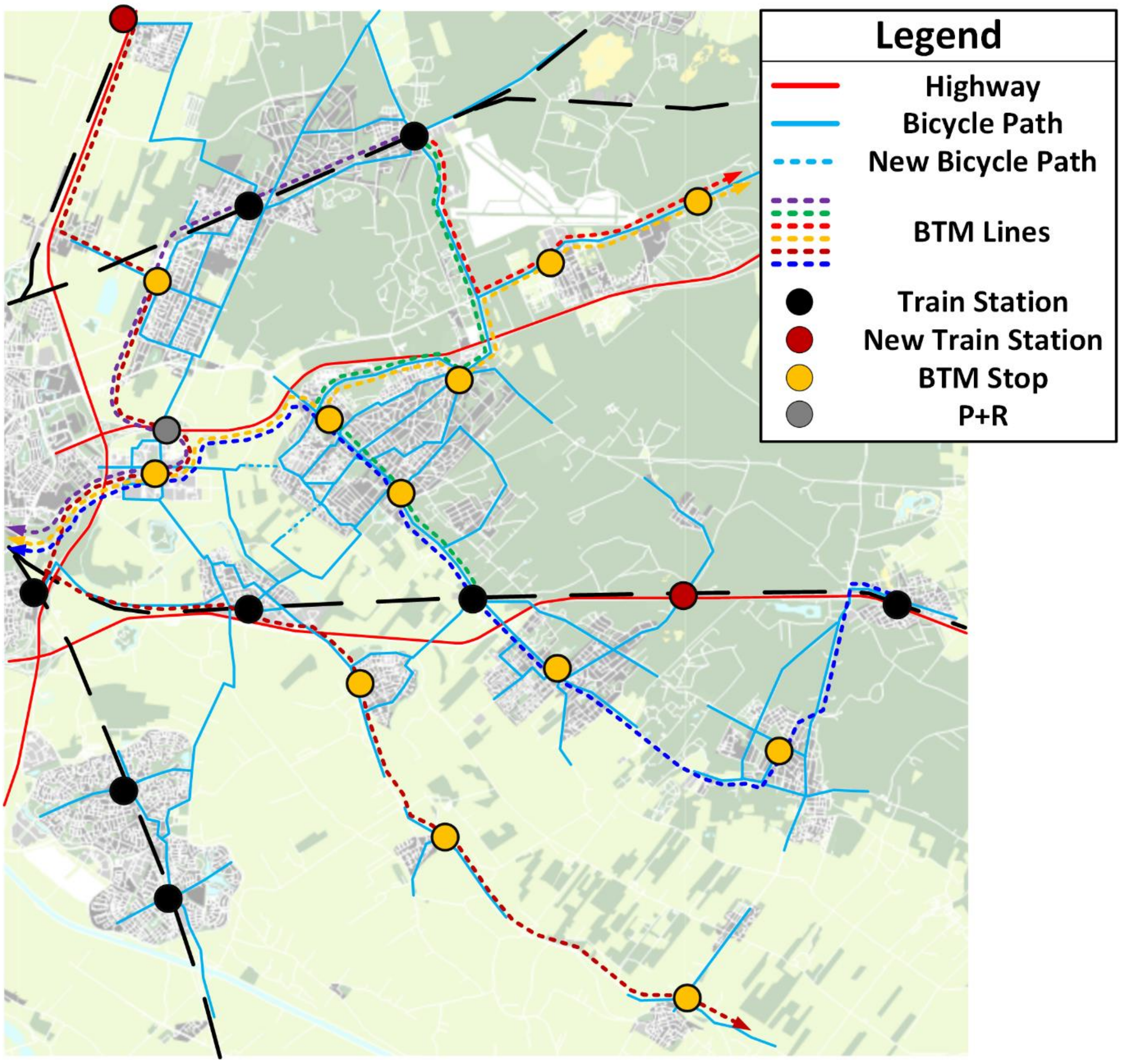


Figure 53 Step 4: design of BTM transit lines

Step 5 and final results
With the completion of the transit lines, the bicycle network can be finalized which completes the design of the multimodal network. In Figure 54, the final multimodal network design is shown. To smoothen the bicycle network, some bicycle corridors are extended and connected to each other.
After smoothing the bicycle network. The multimodal network with the bicycle as core for the USP case study area is now complete. In the final design, two bicycle paths/corridors, two train stations, 12 BTM stops, and six BTM lines are added or extended. In Figure 55, a schematic overview of the BTM lines is shown. This figures shows a ring-radial (high level) transit network with Utrecht CS in central position.
It should be noted that especially for the BTM locations, hundreds of alternatives can be imagined. Some of them may be better than the alternative shown in Figure 54. The determined locations for BTM stops should be more seen as a first approximation. If it is more suitable to relocate to a

neighbouring street, it will have little impact on the results. Only if the relocation is more than several hundred meters, it could have an impact on the results.
For this thesis however, it is mainly about to what extent a multimodal network with the bicycle as core improves the total travel time for the traveller, and the share of bicycle and transit in the modal split.

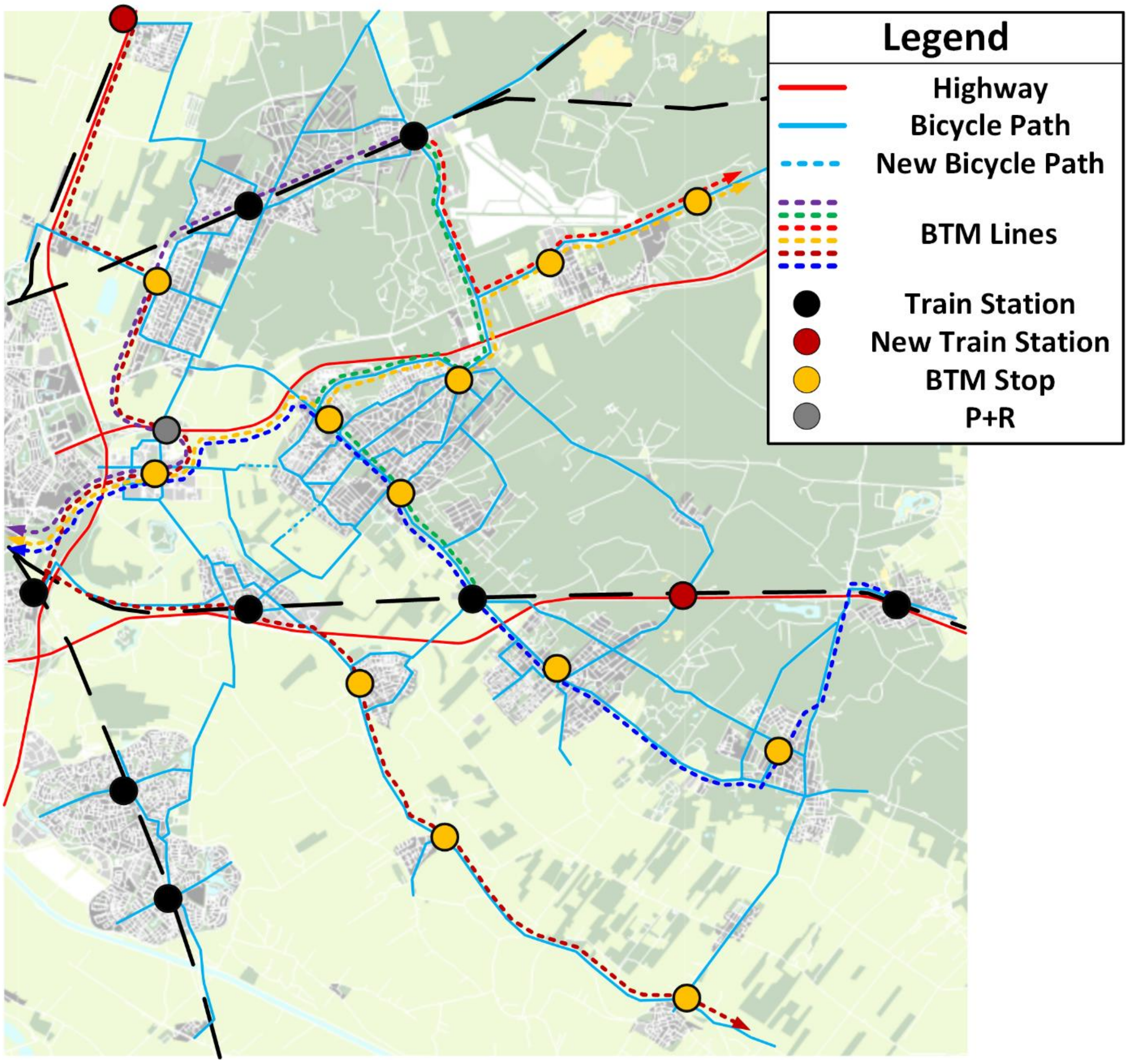


Figure 54 Final multimodal network design Basic alternative

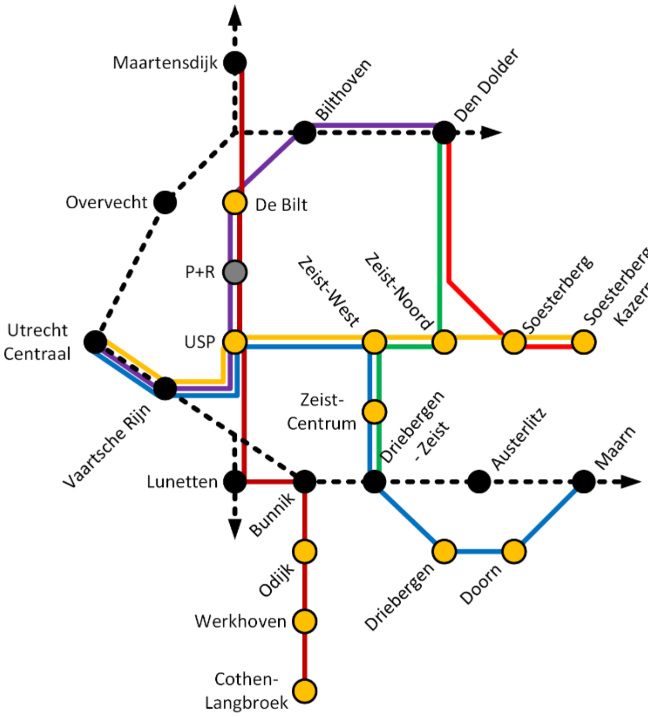


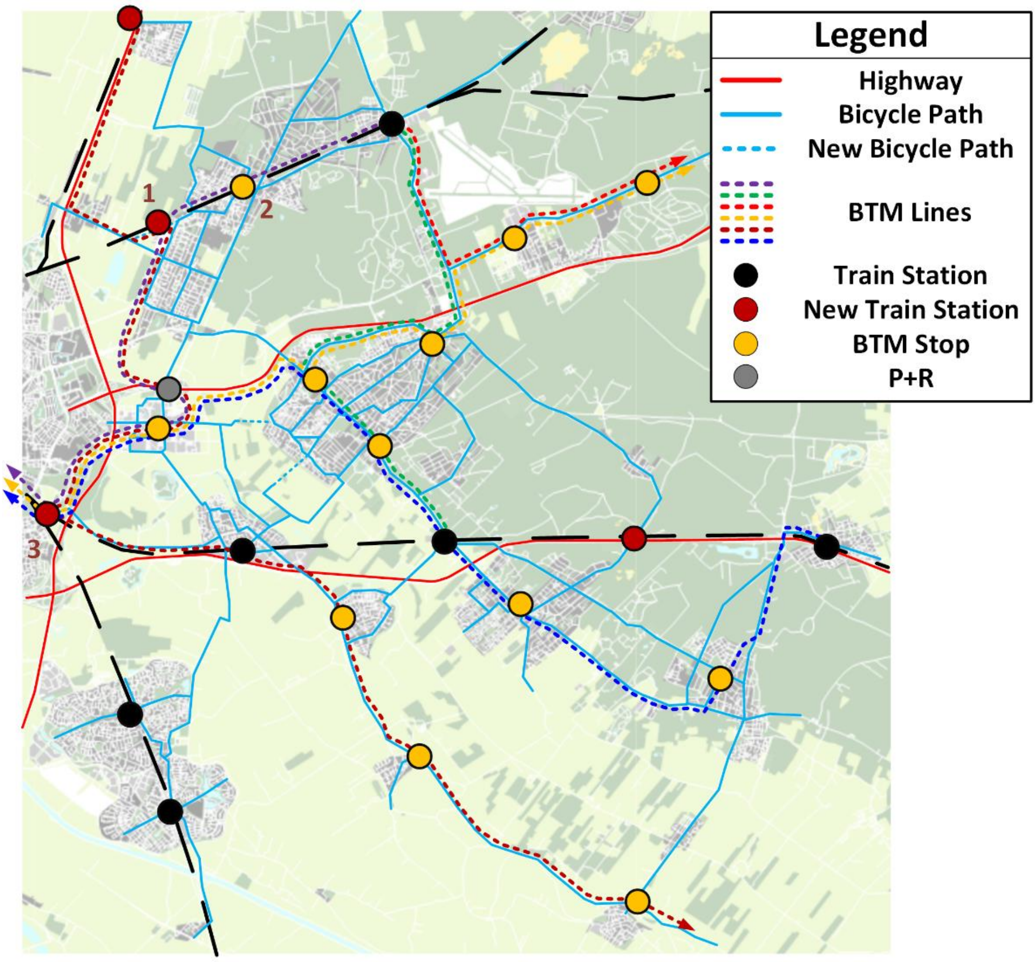
Figure 55 "metro map" style BTM network Basic alternative

Plus Alternative

As stated at the beginning of this chapter, the plus alternative also tries to unburden Utrecht Centraal and the Uithoflijn by adding feeder stations. This is done by making several additions in the Basic alternative. In the Figures 56 and 57, the Plus alternative is shown.

The first change is the implementation of train station De Bilt instead of the BTM stop. At this station, Intercity trains will also stop. With this feeder station, travellers from the north-eastern part of the Netherlands can transfer to a BTM mode and travel to the USP. Main reason for implementing this station instead of upgrading station Bilthoven is the limited available area space in Bilthoven. Due to the new train station, station Bilthoven is downgraded to a BTM stop. Another adjustment is the relocation of train station Lunetten. This station has been moved more to the west where the train tracks from the south and east merge. Furthermore, sprinters and intercity trains will stop at Lunetten. By placing Lunetten at this location, travellers from the western, eastern and southern part of the Netherlands can transfer, to a BTM line for travelling to the USP. To increase the capacity at the transit corridor Lunetten-USP, BTM lines purple, yellow, and blue will also stop at Lunetten.

With the Feeder-stations Lunetten, De Bilt, and to a lesser degree Maartensdijk, less train travellers will travel through Utrecht Centraal when travelling to USP. This may unburden Utrecht Centraal and the Uithoflijn significantly. Downside of implementing these feeder station is that it creates extra travel time for through-going train travellers.



1: De Bilt
2: Bilthoven
3: Lunetten

Figure 56

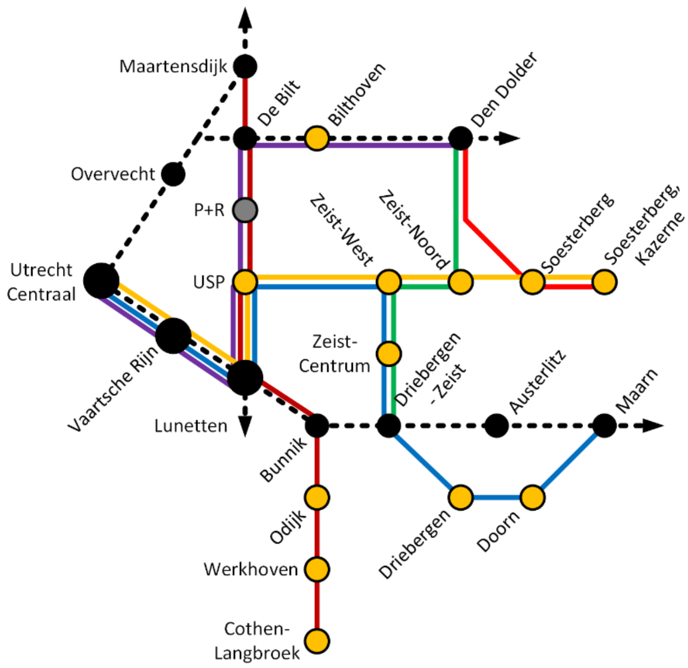


Figure 57

4.3 VRU MODEL

As stated earlier, the VRU model is used to simulate trips in the case study area. The original model consists of a 2015 and 2030 scenario. For this case study, the 2030 scenario is used. Main reason is the presence of the Uithoflijn, which is absent in the 2015 scenario. Furthermore, the travel demand is higher in 2030. The original transport network in the 2030 scenario is also used as zero-alternative during the case study.
In the VRU model, some values and assumptions are different from the information found in the literature study. The next paragraphs describes the differences and how it is eventually implemented.

Limitations Simulation Software

The VRU model runs on the simulation software called Omnitrans (version 6.1), which is a trip-based static simulation software based on the 4-step model[IX]. With the VRU model, trips within the province of Utrecht can be simulated.
As the 4-Step model first calculates the mode choice for each trip followed by route assignment, this approach is outdated for simulating multimodal trips. Simulating these trips requires an approach in which the mode choice and route assignment are combined. However, no simulation software capable of doing this at a large scale, currently exist. Therefore, the VRU model with the Omnitrans software is the only option for this case study. In the next paragraph, it is discussed how the VRU model simulates multimodal trips in the mode choice.

Mode choice in VRU

In the VRU model, the possible mode choices for a full trip are car, transit (including multimodal) or bicycle (regular bicycle). The transit mode consists of different sub-mode choice combinations. Each combination has a different access or egress mode, which are:

1) Car ⇔ Transit ⇔ Bicycle
2) Car ⇔ Transit ⇔ Walk
3) Walk ⇔ Transit ⇔ Bicycle
4) Bicycle ⇔ Transit ⇔ Walk
5) Bicycle ⇔ Transit ⇔ Bicycle
6) Walk ⇔ Transit ⇔ Walk

When the (main) mode choice is transit, a sub-mode choice combination is also chosen. The VRU model calculates for every (sub-)mode choice the skim matrix. Based on these matrices, the mode choice for a certain trip is determined. In the model, only the regular bicycle is included. In order to include E-bike and shared-bike, more mode choices need to be included. This requires making changes in the technical core of the model. Therefore, it is decided to only use the regular bicycle (values) in this case study. So, the egress trips are also done on regular bicycles.
When the car is the main mode, the model always assumes a door-to-door car trip. So, the bicycle as egress from a P+R is not possible in the model without a transit link in between (which makes the car an access mode instead of main mode).

To determine the mode choice (combinations), the model has several conditions. These conditions are enumerated below including, if needed, references to the enumerations above. All of the mentioned conditions are to prevent 'illogical' trips like using the car for a 1 minute access trip, which will (almost) never occur in reality.

- Exclude 4 & 5 if bicycle access trip is shorter than 2 minutes.
- Exclude 1 & 2 if car access trip is shorter than 5 minutes.

[IX] Trip Generation => Trip Distribution => Mode choice => Route Assignment

- Exclude sub-mode choice if egress trip (car, bicycle, or walk) is longer than 20 minutes
- Exclude trip if bicycle/transit-ratio is larger than 1
- Exclude trip if walk/transit-ratio is larger than 0,8
- Exclude transit trips shorter than 1,5 minutes

When comparing the above mentioned conditions with the values determined and used in this thesis, the model has fewer and less strict conditions. Furthermore, the model does not make a distinction in stop/station type when determining the maximum range of cyclists. However, using the values determined in this thesis into the model is very difficult as it requires changing the technical core of the model. Therefore, the above mentioned conditions are not changed. As far as known, the model does not use a maximum door-to-door cycling distance or cycling trip time.

Experienced Travel Time
In the literature study, the experienced travel time was studied. Eventually several multiplier values and penalties were determined to express the attractiveness of certain trips. In the VRU model/Omnitrans, it is not possible to apply the multiplier values used to calculate the experienced travel time. The software calculates only the "real" travel time. Instead, the attractiveness of the modes are determined by an utility function. The only experience factor implemented separately in the model is the transfer penalty. Therefore, only the transfer penalty (5,5 min) is implemented in the model for transfers between transit modes. For consistency reasons, a transfer between the car and transit is also 5,5 min. For transferring between cycling/walking and transit or car does no penalty is applied.
Due to the absence of the experienced travel time, it is more difficult to determine if the designed network fits within the preferences of the traveller.

Existing transit lines
In the VRU model, many bus lines are present. Originally, the designed multimodal network for this case study would replace the bus lines. However, as the VRU model simulates the trips for the whole province, simply removing them has a large negative impact for other areas in the province. An alternative is ending the lines at the border of the case study area. Even then, there is a possibility of negative effects for zones outside the case study area. Therefore, it is decided to keep the existing bus lines in the model. Consequently, it is not possible to determine whether applying the designed transit network is cheaper to operate than the existing transit network. It is only possible to make a first indication about the cost of applying this multimodal network in the USP area. Keeping the existing bus lines also may influence the travel time results and mode choice. Some travellers may use a regular bus line for travelling to the new BTM lines, instead of the bicycle. However, the expectation is that this occurrence will be limited due to the transfer penalty when transferring between transit modes.

Implementation of BTM lines into the model
BTM vehicles can operate in both mixed traffic lanes and dedicated lanes/tracks. For a good punctuality and regularity score, dedicated lanes are preferred as mixing with other traffic has a higher chance of obstructions like traffic jams. Therefore, the BTM lines are implemented into the model with dedicated lanes. To reflect the number of intersections, urban density and limitation of noise pollution on a certain trajectory, these dedicated lanes have different maximum speed limits. Generally, the following speed limits are applied:

- 90 km/h for trajectory to Maartensdijk next to the A27 and train tracks
- 70 km/h when outside the urban area
- 50 km/h next or in the outskirts of a village/city
- 40 km/h through a city/village
- 30 km/h for trajectories through a small street

Each implemented BTM service line has a frequency of 6 departures per hour per direction during the whole day. During the simulations, the frequency is only used to determine the waiting time. The capacity of the vehicles is unlimited. In the model, the waiting time of travellers is always 25 % of the interval between departures. In the theoretical scenarios, it was 50 %. However, changing the factor in the model has a large negative consequence for transit services with a frequency of 2 departures per hour per direction (waiting time of 15 min instead of 7,5). As it is not possible to set a fixed waiting time for transit services with a low frequency, the original waiting time factor of the model is used.

In the VRU model, a specific mode type to each transit line needs to be chosen. As the purple line in both alternatives (Figures 55 & 57) is an extension of the Uithoflijn, trams/light-rail are applied. For the other lines, the bus/BRT[X] is used. As far as known, the mode type does not influence the mode- and route-choice. However, transit in general has a negative preference constant in the utility function of the mode choice.

Other comments
In the literature study, it was found that the average cyclist has an average travel speed of 12,5 km/h. In the VRU model, the travel speed of the cyclist is dependent on the infrastructure (often between 12 and 14 km/h). As this may better reflect the travel speeds of cyclists, the values in the model are not changed.
The VRU modes simulates three time periods, namely: morning rush hours, evening rush hours, and rest of day. The time period of both rush hours is two hours.
During this thesis, the Dutch government started studying the possibilities of implementing road pricing for car use. If road pricing will be implemented in the Netherlands, large changes in car use are expected. As this thesis started with the assumption of the current system, no road pricing is implemented. If the plans will continue, new simulations including road pricing are needed.

4.4 RESULTS

After implementing both alternatives into the VRU model, trip simulations were made. In the next paragraphs, the simulation results of both alternatives and the Zero alternative are shown, compared, and discussed. As stated earlier, no changes in the network are made in the Zero alternative.

4.4.1 Zero Alternative

After simulating the Zero alternative, several result types were obtained. In Table 43 & 44, the modal splits during the morning rush hours for three zones in the USP are shown. These three zones all have (much) higher influx of travellers during the morning rush hours. Therefore, only these three zones are considered. The locations of these zones are shown in Figure 58. The travel times from different cities to the USP are shown in Table 45.

[X] Bus Rapid Transit

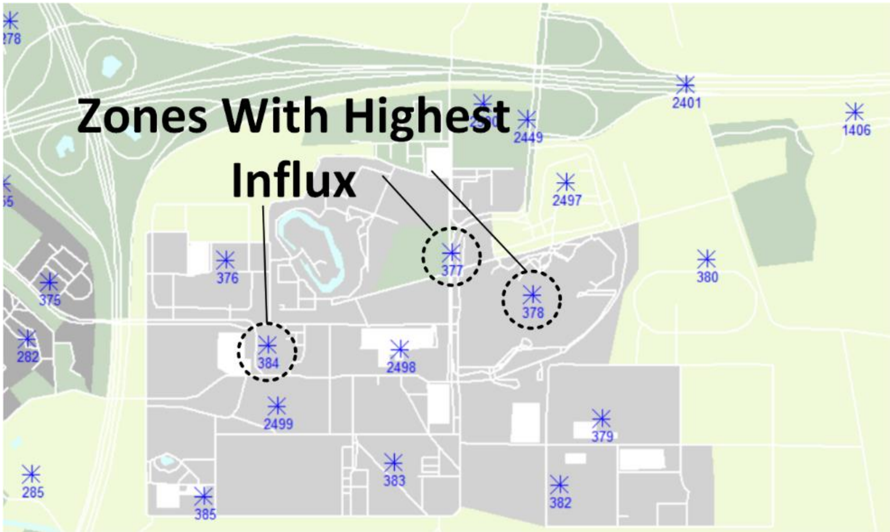


Figure 58 Locations zones with highest influx during morning rush hours

The modal split values are separated into two tables. Table 43 shows for each main mode the number of users for trips to the three zones. The main modes are car, bicycle and transit. Transit also includes the multimodal trip combinations car-transit and bicycle-transit. In Table 44, the transit mode is split up into access-egress mode choice combinations. So, 'Bicycle-Walking' means that the traveller used the bicycle as access mode, transit as main mode, and walking as egress mode for travelling to the USP. As Table 43 indicate, the transit mode is by far the most used main mode for trips to the USP. In total, approximately 70 percent of all morning rush hour trips are by transit. This seems very high. However, it should be noted that many students with a student-transit card[XI] travel on a daily base to the USP. This can explain the high amount of transit users.
When looking into the access and egress mode choices of these transit trips (Table 44), the bicycle as access and walking as egress are the most common (53,2 %). Furthermore, over 80 percent of all transit trips are already bicycle-transit trips. Another interesting observation are the high amount of travellers using the bicycle as egress mode. A possible cause is the method the model uses to simulate the mode choice including the egress mode. It is likely that the model does not reflects the bicycle use as egress mode correctly.
Overall, most travellers already have a multimodal trip. Still, almost 8000 travellers (20 %) use the car for travelling to the USP during the morning rush hours. Therefore, there is still possibility for improvement.

Table 43 Modal Split several USP zones during the morning rush hours with Zero alternative

	Car		Bicycle		Transit		Total	
Zone Number	#	%	#	%	#	%	#	%
384	5540	19,3	1510	5,3	21670	75,5	28720	100
378	1370	22,5	1830	30,0	2900	47,5	6100	100
377	820	19,0	880	20,4	2620	60,6	4320	100
Total	7730	19,7	4220	10,8	27190	69,5	39140	100

Table 44 modal split access and egress combinations for transit trips to USP during morning rush hours with Zero alternative

	Car-Bicycle		Car-Walking		Bicycle-Walking		Walking-Walking		Walking-Bicycle		Bicycle-Bicycle		
Zone	#	%	#	%	#	%	#	%	#	%	#	%	Total
384	280	1,3	950	4,4	12190	56,3	4470	20,6	680	3,1	3080	14,2	21650
378	80	2,8	70	2,4	940	32,9	350	12,2	400	14,0	1020	35,7	2860
377	40	1,5	90	3,5	1280	49,4	420	16,2	190	7,3	570	22,0	2590
Total	400	1,5	1110	4,1	14410	53,2	5240	19,3	1270	4,7	4670	17,2	27100

[XI] Dutch students can use the (Dutch) transit for free (there are some limitations)

In Table 45, the total travel time of different cities/zones to the USP is shown. From each city, one zone is chosen (except Zeist with three zones) as representative zone. Between these zones and the USP, the travel times with different modes (combinations) are calculated. The modes (combinations) are: Car, Bicycle, Bicycle-Transit-Walking, Walking-Transit-Walking, Walking-Transit-Bicycle, and Bicycle-Transit-Bicycle.
According to these results, the car-only trips to the USP are always faster than the other options. For zones/cities located close to the USP, the bicycle is often a faster mode than a transit trip. The relative time difference between the car and transit trip depends on the origin of the zone. From some zones, the transit trips are "only" two times slower than the car trips. For several other zones, the transit trips are more than four times slower. On average, a bicycle-transit-bicycle trip is 2,8 times slower than the car trip. It should be noted that the model uses a BPR-function to calculate travel time delay caused by traffic jams. Furthermore, the parking time is not included. Therefore, the travel time during rush hours with the is probably higher in practice.
For most trips, the bicycle as access and/or egress mode has a (slightly) positive impact on the total travel time of a transit trip. It confirms the advantages of combining the bicycle and transit modes in a multimodal trip.

Table 45 Travel times to USP zone 384 per mode (combination) in Zero alternative

		Car	Bicycle		B-W		W-W		W-B		B-B	
City	Zone	min	min	/	min	/	min	/	min	/	min	/
Maartensdijk	1368	13	52	4,0	53	4,1	59	4,5	58	4,5	53	4,1
Bilthoven	1418	14	38	2,7	36	2,6	51	3,6	51	3,6	34	2,4
Den Dolder	1611	13	47	3,6	59	4,5	56	4,3	56	4,3	59	4,5
De Bilt	1496	10	25	2,5	27	2,7	46	4,6	41	4,1	25	2,5
Groenekan	1402	11	33	3,0	39	3,5	46	4,2	45	4,1	38	3,5
Soesterberg	2100	13	50	3,8	40	3,1	42	3,2	40	3,1	38	2,9
S'berg, Kazerne	2089	15	64	4,3	50	3,3	53	3,5	50	3,3	48	3,2
Zeist-West	1738	13	23	1,8	33	2,5	39	3,0	37	2,8	31	2,4
Zeist-Noord	1687	13	38	2,9	41	3,2	53	4,1	51	3,9	39	3,0
Zeist-Oost	1698	16	42	2,6	46	2,9	59	3,7	59	3,7	44	2,8
Austerlitz	1626	16	56	3,5	60	3,8	64	4,0	62	3,9	59	3,7
Driebergen	1800	18	53	2,9	50	2,8	55	3,1	54	3,0	51	2,8
Doorn	2266	23	72	3,1	61	2,7	69	3,0	70	3,0	59	2,6
Maarn	2252	21	79	3,8	40	1,9	43	2,0	43	2,0	41	2,0
Bunnik	1585	11	19	1,7	29	2,6	31	2,8	31	2,8	29	2,6
Odijk	1597	17	39	2,3	41	2,4	51	3,0	50	2,9	40	2,4
Werkhoven	1531	18	51	2,8	44	2,4	49	2,7	50	2,8	43	2,4
Cothen	2343	23	76	3,3	49	2,1	53	2,3	54	2,3	48	2,1
Langbroek	2361	23	74	3,2	54	2,3	59	2,6	58	2,5	54	2,3
Average				3,1		2,9		3,4		3,3		2,8

The Zero alternative shows that most of the travellers to the USP already use the transit as main mode. A lot of these trips consist of the bicycle as access and/or egress mode. Still, almost 8000 travellers (20%) use the car as main mode. The travel times of several zones in the case study area indicate that a (multimodal) transit trips is slower than a car trip.

4.4.2 Basic Alternative

Like for the Zero alternative, the modal split values for morning rush hour trips to the USP with the Basic alternative are calculated (Table 46). Compared to the Zero alternative, several significant differences are seen. With the Basic alternative, 2000 more trips are completed the transit as main mode. All other main modes show a decrease. Around 1350 of these trips were first done by door-to-door car trips. So, the implementation of the designed multimodal network has a positive impact on decreasing car use.

Table 46 Modal split several USP zones during morning rush hours with basic alternative

Zone	Car #	Car %	Bicycle #	Bicycle %	Transit #	Transit %	Total #	Total %
384	4500	15,6	1260	4,4	23060	80,0	28820	100
378	1230	20,1	1650	27,0	3230	52,9	6110	100
377	660	15,2	790	18,2	2890	66,6	4340	100
Total	6390	16,3	3700	9,4	29180	74,3	39270	100

Also access and egress modes in transit trips have changed as shown in Table 47. Overall, combinations with walking as egress show a decrease in number of trips. Combinations with the bicycle as egress show an increase in number of trips. It seems that a lot of travellers have changed their egress mode, but keep the same access mode. A likely cause is the location of the new BTM stops, which are further away of their destination zones. The extra transit trips mostly had the bicycle as access and egress mode.

Table 47 modal split access and egress combinations for transit trips to USP during morning rush hours with basic alternative

Zone	Car-Bicycle #	Car-Bicycle %	Car-Walking #	Car-Walking %	Bicycle-Walking #	Bicycle-Walking %	Walking-Walking #	Walking-Walking %	Walking-Bicycle #	Walking-Bicycle %	Bicycle-Bicycle #	Bicycle-Bicycle %	Total
384	870	3,8	410	1,8	9320	40,5	3050	13,2	2150	9,3	7230	31,4	23030
378	140	4,4	30	0,9	710	22,2	240	7,5	520	16,3	1560	48,8	3200
377	40	1,4	110	3,8	1540	53,7	430	15,0	170	5,9	580	20,2	2870
Total	1050	3,6	550	1,9	11570	39,8	3720	12,8	2840	9,8	9370	32,2	29100

The total travel time results are shown in Table 48. Compared to the Zero alternative, all zones have a decrease of the travel time when using a transit trip. On average, a bicycle-transit-bicycle trip is with the basic alternative only 1,7 times slower than the car trip. This is an improvement of more than one point. Also the transit trips with walking as access mode show a significant improvement. When using the bicycle as access mode, the travel time with transit is often less than two times larger than the travel time by car. In the Zero alternative, this is only seen in one zone. The results also suggest show effectiveness of using the bicycle as access mode for reducing the travel time. This impact is smaller for the bicycle as egress mode.

Table 48 Travel times to USP zone 384 per mode (combination) in Basic alternative

City	Zone	Car min	Bicycle min	Bicycle /	B-W min	B-W /	W-W min	W-W /	W-B min	W-B /	B-B min	B-B /
Maartensdijk	1368	13	52	4,0	25	1,9	38	2,9	35	2,7	23	1,8
Bilthoven	1418	14	38	2,7	26	1,9	50	3,6	48	3,4	23	1,6
Den Dolder	1611	13	47	3,6	29	2,2	48	3,7	46	3,5	27	2,1
De Bilt	1496	10	25	2,5	20	2,0	33	3,3	31	3,1	18	1,8
Groenekan	1402	11	33	3,0	23	2,1	44	4,0	42	3,8	21	1,9
Soesterberg	2100	13	50	3,8	24	1,8	32	2,5	30	2,3	22	1,7
S'berg, Kazerne	2089	15	64	4,3	27	1,8	29	1,9	27	1,8	25	1,7
Zeist-West	1738	13	23	1,8	21	1,6	34	2,6	32	2,5	19	1,5
Zeist-Noord	1687	13	38	2,9	23	1,8	31	2,4	30	2,3	21	1,6
Zeist-Oost	1698	16	42	2,6	28	1,8	43	2,7	41	2,6	26	1,6
Austerlitz	1626	16	56	3,5	37	2,3	51	3,2	45	2,8	35	2,2
Driebergen	1800	18	53	2,9	28	1,6	32	1,8	29	1,6	24	1,3
Doorn	2266	23	72	3,1	32	1,4	42	1,8	40	1,7	30	1,3
Maarn	2252	21	79	3,8	36	1,7	38	1,8	36	1,7	34	1,6
Bunnik	1585	11	19	1,7	24	2,2	31	2,8	31	2,8	21	1,9
Odijk	1597	17	39	2,3	27	1,6	43	2,5	41	2,4	25	1,5
Werkhoven	1531	18	51	2,8	29	1,6	36	2,0	33	1,8	27	1,5
Cothen	2343	23	76	3,3	34	1,5	46	2,0	44	1,9	32	1,4
Langbroek	2361	23	74	3,2	39	1,7	44	1,9	42	1,8	37	1,6
Average				3,1		1,8		2,6		2,5		1,7

Also results on the use of the implemented multimodal network are obtained. In Table 49, the number of travellers boarding or alighting at a BTM stop or a new train station during morning rush hours are shown. In the table, a distinction is made between travellers arriving/departuring by bicycle or walking. If applicable, the number of travellers transferring between train and BTM are also shown. Figure 59 shows the intensity values of most BTM trajectories during the morning rush hours.
According to the results shown in Table 49, all stops and stations attract hundreds of travellers during the morning rush hours. At some stops, this is even more than 1000 travellers. Furthermore, it is noticeable that a lot of travellers transfer from train to BTM (except Station Maarn). For most stops and stations, the number of travellers arriving or departing by bicycle is much higher than by walking, and highest at BTM stop Zeist-West.

Table 49 Number of travellers boarding, alighting or transferring at stop or station per mode during rush hours

	Bicycle		Walking		Transfer between transit modes	
Stop/Station	Boarding	Alighting	Boarding	Alighting	To train	To BTM
Station Maartensdijk (Train)	500	540	60	80	130	1000
Station Maartensdijk (BTM)	220	60	30	20	-	-
Station Bilthoven (BTM)	580	250	70	40	10	2140
Station Den Dolder (BTM)	370	280	150	70	460	1030
De Bilt	900	440	70	70	-	-
Soesterberg	620	240	180	130	-	-
Soesterberg, Kazerne	30	320	190	140	-	-
Zeist-West	2530	1400	130	270	-	-
Zeist-Noord	780	1080	90	160	-	-
Zeist-Centrum	1060	1020	170	280	-	-
Station Bunnik (BTM)	350	160	90	70	380	290
Station Driebergen-Zeist (BTM)	260	330	160	200	270	1730
Driebergen	970	260	380	90	-	-
Station Austerlitz (Train)	570	600	40	0	-	-
Doorn	480	330	290	70	-	-
Station Maarn (BTM)	100	30	20	10	120	100
Odijk	420	130	90	90	-	-
Werkhoven	180	70	100	40	-	-
Cothen-Langbroek	310	90	40	10	-	-
Lunetten (BTM)	550	250	750	170	280	650

As stated, the traveller intensity values of trajectories during the morning rush hours per direction are shown in Figure 59. The black nodes are train stations and yellow nodes are BTM stops. The train lines are not shown. While not as high as the Uithoflijn (tram from Utrecht CS to USP and P+R), several trajectories to the USP have a high intensity. These values indicate a high attractiveness for operators to operate a transit-service on these routes. These values can be higher when extending some of the BTM lines to Amersfoort and Wijk Bij Duurstede (both outside the case study area).

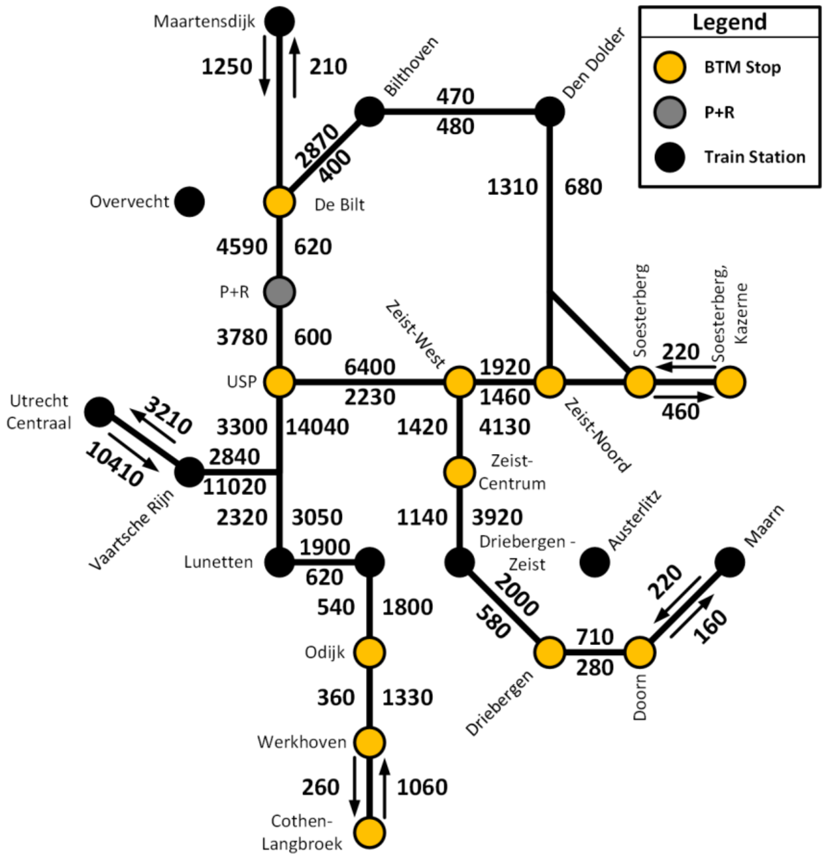


Figure 59 intensities at trajectories per direction during morning rush hours

The simulation results of the Basic alternative give insight in the effects of implementing a multimodal network with the bicycle as core element on travel patterns. Compared to the Zero alternative, several improvements are seen. Firstly, more than 1000 travellers switched from the car as main mode trip to a transit trip. Furthermore, the travel time of the transit trip has decreased all zones. The modal split also showed a high popularity of using the bicycle as access and/or egress mode, shown by the increased boarding and alighting numbers of each new BTM stop and train station. The implementation of the multimodal network was not only beneficial for citizens within the case study area, as also for the train travellers transferring between the train and BTM. This indicates the attractiveness of the BTM lines for the train travellers to the USP area.

4.4.3 Plus Alternative

In this paragraph, the simulation results of the Plus alternative are shown. The modal split values are shown in Table 50 & 51. Compared to the Basic alternative, the differences in the main mode modal split are very small. Apparently, the implementation of the extra feeder stations do not have an impact on the modal split of the main modes. Also the impact on the access and egress combinations in Table 51 is small. However, the combinations with walking as egress mode became are more often used. Overall, the implementation of the Lunetten and De Bilt feeder station did not create a higher modal shift to transit compared to the basic alternative, for travellers to the USP.

Table 50 Modal split several USP zones during morning rush hours with the Plus alternative

	Car		Bicycle		Transit		Total	
Zone	#	%	#	%	#	%	#	%
384	4480	15,5	1250	4,3	23100	80,1	28830	100
378	1220	20,0	1630	26,7	3260	53,4	6110	100
377	640	14,7	780	18,0	2920	67,3	4340	100
Total	6340	16,1	3660	9,3	29280	74,5	39280	100

Table 51 modal split access and egress combinations for transit trips to USP during morning rush hours with Plus alternative

Zone	Car-Bicycle #	Car-Bicycle %	Car-Walking #	Car-Walking %	Bicycle-Walking #	Bicycle-Walking %	Walking-Walking #	Walking-Walking %	Walking-Bicycle #	Walking-Bicycle %	Bicycle-Bicycle #	Bicycle-Bicycle %	Total
384	720	3,1	540	2,3	9750	42,2	3140	13,6	2070	9,0	6860	29,7	23080
378	140	4,3	40	1,2	690	21,3	250	7,7	520	16,0	1600	49,4	3240
377	40	1,4	110	3,8	1510	52,2	440	15,2	160	5,5	630	21,8	2890
Total	900	3,1	690	2,4	11950	40,9	3830	13,1	2750	9,4	9090	31,1	29210

In Table 52, the travel times to the USP (zone 384) per travel mode (combination) are shown. Compared to the basic alternative, the travel times have not changed significantly.

Table 52 Travel times to USP (Zone 384) per mode (combinations) with the Plus alternative.

City	Zone	Car min	Bicycle min	Bicycle /	B-W min	B-W /	W-W min	W-W /	W-B min	W-B /	B-B min	B-B /
Maartensdijk	1368	13	52	4,0	26	2,0	39	3,0	36	2,8	24	1,8
Bilthoven	1418	14	38	2,7	26	1,9	50	3,6	48	3,4	23	1,6
Den Dolder	1611	13	47	3,6	30	2,3	49	3,8	47	3,6	28	2,2
De Bilt	1496	10	25	2,5	21	2,1	33	3,3	31	3,1	19	1,9
Groenekan	1402	11	33	3,0	23	2,1	45	4,1	42	3,8	21	1,9
Soesterberg	2100	13	50	3,8	24	1,8	32	2,5	30	2,3	22	1,7
S'berg, Kazerne	2089	15	64	4,3	27	1,8	29	1,9	27	1,8	25	1,7
Zeist-West	1738	13	23	1,8	21	1,6	34	2,6	32	2,5	19	1,5
Zeist-Noord	1687	13	38	2,9	23	1,8	31	2,4	30	2,3	21	1,6
Zeist-Oost	1698	16	42	2,6	28	1,8	43	2,7	41	2,6	26	1,6
Austerlitz	1626	16	56	3,5	34	2,1	48	3,0	46	2,9	32	2,0
Driebergen	1800	18	53	2,9	26	1,4	31	1,7	29	1,6	24	1,3
Doorn	2266	23	72	3,1	32	1,4	42	1,8	40	1,7	30	1,3
Maarn	2252	21	79	3,8	34	1,6	38	1,8	37	1,8	32	1,5
Bunnik	1585	11	19	1,7	23	2,1	30	2,7	30	2,7	20	1,8
Odijk	1597	17	39	2,3	26	1,5	42	2,5	40	2,4	24	1,4
Werkhoven	1531	18	51	2,8	28	1,6	35	1,9	32	1,8	26	1,4
Cothen	2343	23	76	3,3	33	1,4	45	2,0	43	1,9	31	1,3
Langbroek	2361	23	74	3,2	38	1,7	43	1,9	41	1,8	36	1,6
Average				3,1		1,8		2,6		2,5		1,6

The number of travellers boarding and alighting at each BTM stop and new train stations are shown in Table 53. It also shows the number of passengers transferring between the train and BTM. Unlike with the modal split and travel time, large differences between the basic- and Plus alternative can be observed. Largest changes are at the train stations Lunetten and De Bilt. At Lunetten, almost 6000 travellers are transferring from the train to the BTM. In the basic alternative, this was only 650 travellers. A lot of these travellers were likely first transferring at station Driebergen-Zeist, as this station shows as clear decrease in travellers (over 1500). With almost 4000 travellers transferring to the BTM, station De Bilt also becomes a large station in this alternative. In the basic alternative, Bilthoven station had only 2100 travellers transferring to the BTM.
Based on the transfer numbers, the stations Lunetten and De Bilt indeed function as a feeder stationin this alternative.

Table 53 Number of traveller boarding, alighting per access mode and number of travellers transferring in Plus alternative

	Bicycle		Walking		Transfer	
Stop/Station	Boarding	Alighting	Boarding	Alighting	To train	To BTM
Station Maartensdijk (Train)	480	510	60	70	110	860
Station Maartensdijk (BTM)	220	90	30	20	-	-
Station Bilthoven (BTM)	660	460	100	150	-	-
Station Den Dolder (BTM)	360	350	130	90	330	900
De Bilt (Train)	1560	2490	60	50	310	4030
De Bilt (BTM)	690	270	10	10	-	-
Soesterberg	580	200	180	140	-	-
Soesterberg, Kazerne	30	300	120	110	-	-
Zeist-West	2370	1330	170	260	-	-
Zeist-Noord	760	1020	90	160	-	-
Zeist-Centrum	1030	820	150	230	-	-
Station Bunnik (BTM)	370	140	80	60	100	140
Station Driebergen-Zeist (BTM)	300	370	10	10	460	440
Driebergen	960	280	370	100	-	-
Station Austerlitz (Trein)	670	620	10	10	-	-
Doorn	480	330	290	70	-	-
Station Maarn (BTM)	80	30	30	10	110	90
Odijk	530	160	110	100	-	-
Werkhoven	210	80	220	40	-	-
Cothen-Langbroek	370	100	940	340	-	-
Lunetten (BTM)	950	590	10	10	1000	6070

The intensities of travellers at BTM trajectories are shown in Figure 60. Compared to the basic alternatives, some changes are noticeable. At the trajectory Utrecht Centraal to Lunetten, the number of travellers decreases with more than 2000. Between Lunetten and the USP however, the intensity has increased. Apparently, many travellers transfer in the Plus alternative at Lunetten instead of Utrecht Centraal. Also at the trajectory De Bilt-USP, the number of travellers increases with more than thousand. Between the USP and station Driebergen-Zeist, a decrease of around 1500 travellers can be seen. Most of these travellers now probably transfer at station Lunetten instead.

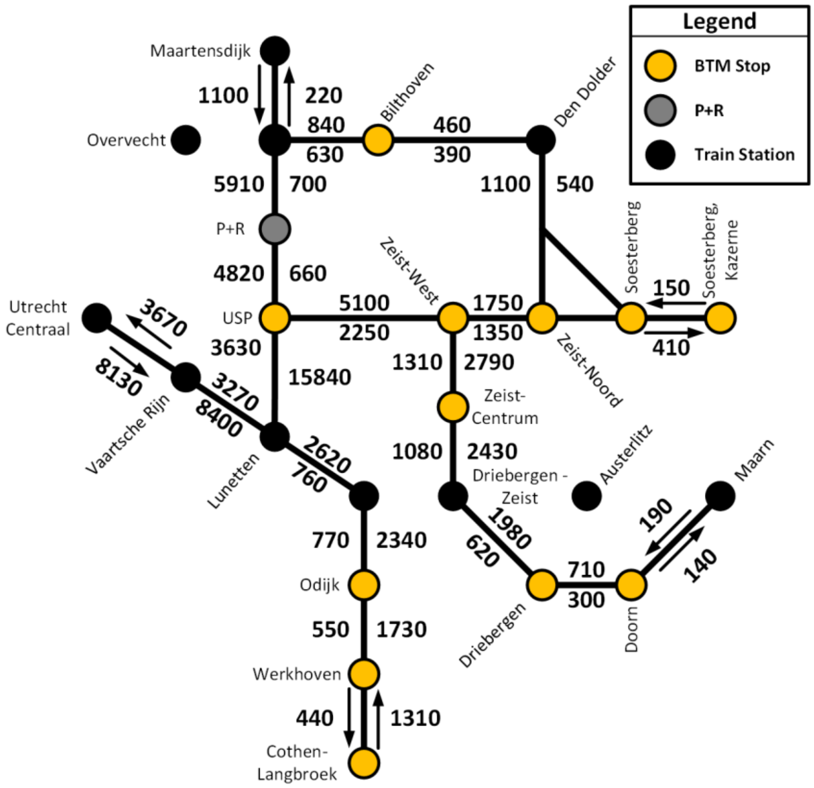


Figure 60 Intensities at trajectories per direction with Plus alternative

4.5 CONCLUSION

This case study was used to improve (multimodal) transit trips for the USP and its surrounding area, answering the following sub- and main question:

Sub-question: *"To which extent is it possible to decrease car-use by applying a multimodal network with the bicycle as core"*

Main question: "*To which extent does a multimodal passenger transport network with the bicycle as core reduce the total travel time for most travellers and increase the modal split for (multimodal) transit trips, without high investment- and operational cost"*

In both Basic- and Plus alternative, the car use decreased with more than 1300 vehicles (almost 20 %) during the morning rush hour, compared to the Zero alternative. Furthermore, the number of (multimodal) transit users increased with around 2000 travellers (close to 10 %) during the morning rush hours. Based on these numbers, it is possible to say that applying a multimodal network with the bicycle as core will attract more (multimodal) transit users at the expense of car users. Due to limitations of the model (sub-chapter 4.3) and assumptions, it is possible that the results are too optimistic or conservative. Still, it is expected that a multimodal network with the bicycle as core can decrease car-use.

The results of both Basic- and Plus alternative also showed a large decrease of the total travel time for travellers, compared to the Zero alternative. With cycling as access- and egress mode, the transit trips in the Basic, and Plus alternative were only 1,8 times slower than a car trip. For the Zero alternative, it was 2,9. Furthermore, this improvement occurred for all residential zones studied in the case study. Also for other access-egress combinations, the differences between these alternatives were large. Therefore, this case study shows that using the bicycle as core in a multimodal network decreases travel time a lot compared to a walking-transit trip combination.

About the effects on the operational costs, no conclusion could be made as the old bus lines were still operating.

It should be noted that several factors may have had an impact on the simulation results. First, the VRU model and Omnitrans 6.1 have several limitations. It is possible that using a different simulation software gives different results. Therefore, it would be interesting to re do this case study when a new transportation model and simulation software are available. Also keeping the 'old' bus lines may have influenced the results. These can only be removed if a multimodal network with the bicycle as core is designed for the whole Province of Utrecht. During the case study, the focus was mostly on (multimodal) transit trips to the USP and train station. However, there are many other types of OD trips. It is possible that if the old bus lines were removed, an increase of the travel time occurred.

While there where factors influencing the simulation results, it is unlikely this would have resulted in (for instance) an increase in car-use and less (multimodal) transit trips. Therefore, the conclusions are still valid.

4.6 SUGGESTIONS FOR THE PROVINCE OF UTRECHT

This case study introduced several new BTM lines, BTM stops and train stations for the area around the USP. This new infrastructure had a large impact on the travel routes and -modes of the travellers. For both Basic- and Plus alternative, most BTM stops attracted several hundreds of travellers arriving by bicycle during the morning rush hours. At BTM stop 'Zeist-West', it was even more than 2000 travellers. It shows that many travellers are willing to use a bicycle-BTM trip combination instead of the 'old' walk-transit trip combination. Therefore, it can be interesting for the Province of Utrecht and its municipalities to focus more on the bicycle-BTM trip combinations instead of walking-transit.

In both Basic- and Plus alternative, six new BTM service lines were created as shown in Figure 61. Furthermore, the Basic alternative introduced two new train stations. The Plus alternative introduced

four new train stations, of which two were feeder stations. At many BTM trajectories (both Basic- and Plus alternative), more than 1000 travellers were using the BTM during morning rush hours. If the BTM vehicle has a capacity of 90 travellers, a frequency of at least 6 vehicles per hour is needed. These numbers show a high popularity of the introduced BTM lines. The introduced service lines also improved the accessibility of the more isolated areas. In some occasions, the travel time of a (multimodal) transit trip was almost halved. Therefore, it is interesting for the Province to apply these BTM lines as it is not only popular to use, but also improves the accessibility of the more rural areas.
Both alternatives also introduced new train stations at Maartensdijk and Austerlitz along existing train tracks. In the Basic alternative, both stations attracted around 550 travellers during the morning rush hours. Austerlitz attracted almost 700 in the Plus alternative. These values are higher than the existing train stations Bunnik and Driebergen-Zeist. Station Maartensdijk also had around 1000 travellers transferring from train to the BTM line for travelling to the USP. These results indicate the potential of constructing these two train stations. Furthermore, Station Maartensdijk can function as a feeder station. However, it is needed to study the effects of implementing these stations on the train timetable.
A main difference between the Basic- and Plus alternative was the implementation of the feeder stations Lunetten and De Bilt in the Plus alternative. Implementing these two station did not had an impact in increasing the number of transit users for travelling to the USP. However, the number of travellers using the Uithoflijn at Utrecht CS decreased with more than 2000 travellers during the morning rush hours. So, these feeder stations did relieve Utrecht CS and the Uithoflijn. As the results are mixed, it cannot stated that constructing the feeder stations Lunetten and De Bilt is beneficial. It will largely depend on the other objectives of the responsible administrations.

While there are several limitations, this case study has shown the potential benefits of applying a multimodal network with the bicycle as core for the Province of Utrecht and its municipalities. The results show that focussing on a bicycle-transit combination improves the accessibility of the area and the USP, and decreases the car-use. However, further research is needed in which the old bus lines are removed and the multimodal network with the bicycle as core is applied at a larger scale.

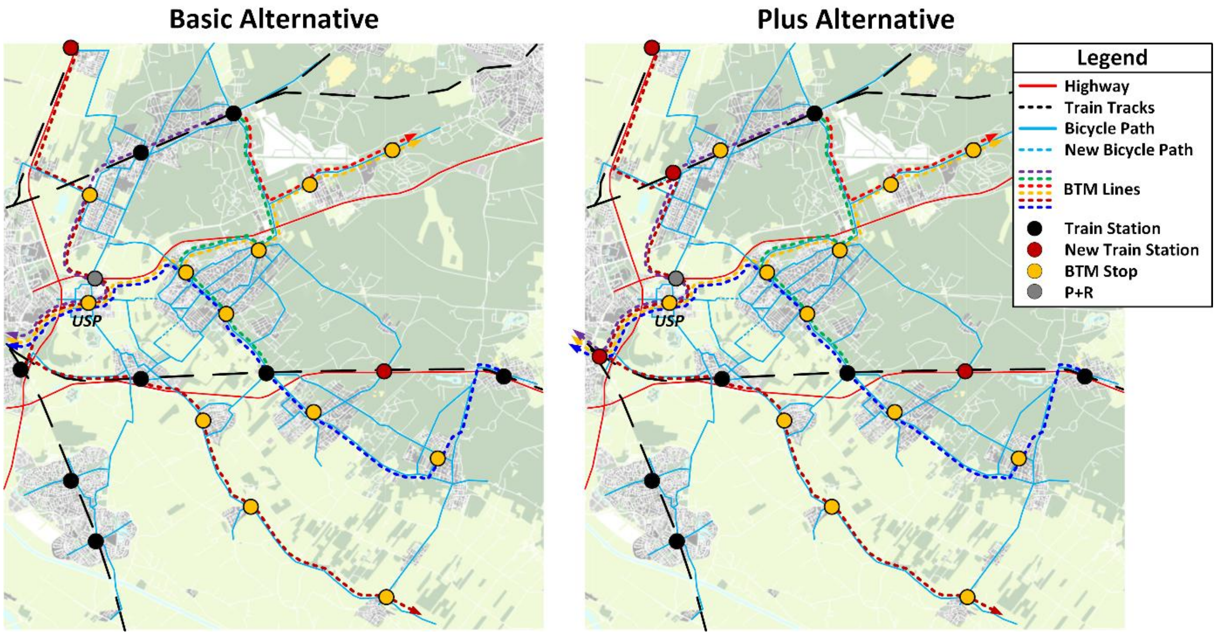


Figure 61 Basic- and Plus alternatives

5 Conclusion, Discussion & Recommendations

With the completion of the case study, a main conclusion about designing a multimodal network with the bicycle as core can be made. In this chapter, the main conclusion, discussion and recommendations are formulated.

5.1 Conclusion

The main goal of this study was to make multimodal passenger transport more attractive, by designing a multimodal network with the bicycle as core of the network. With this approach, passengers use the bicycle combined with transit which could create a lower travel time and decreased car-use, without high operational cost of the transit system.

Based on the goals, the main research question of this study was: "*To what extent does a multimodal passenger transport network with the bicycle as core reduce the total travel time for travellers and increase the modal split for (multimodal) transit trips, without high investment- and operational cost*".

During this thesis, a lot of information and results were obtained about different aspects of multimodal transport. The literature study showed that the catchment area for BTM stops, train stations and P+R were different. Furthermore, the bicycle type (regular, E-bike and shared-bike), and quality of the stop influenced the catchment radius. The study about the trip preferences of the traveller gave useful values to determine the experienced travel time. With the experienced travel time, the preferences of the traveller could be incorporated. Furthermore, the preferences indicated a high disutility for waiting time and transferring between transit vehicles. Therefore, transit trips with a high frequency and few or no transfers are preferred. The literature study of the multimodal network & -service outlines showed three main multi-level services named, Express, Zone, and Trunk-Feeder. Combining these services with the bicycle as access and egress, less stops are needed.

One of the knowledge gaps was the effect of different bicycle catchment radius values and (multi-level) BTM services on the total (experienced) travel time, connection quality and costs. Therefore, scenarios were developed to do some small experiments. It appeared that if the BTM stop was located at the opposite direction of the destination (upstream), a bicycle access trip distance of more than 1000 m had a large negative impact on the (experienced) travel time. However, this impact is smaller for long travel distances. If the stop was located in the same direction of the destination (downstream), the maximum travel distance willingness of 2000 m for BTM stops had a positive impact on the results. Combined with the BTM services, the traditional (no stop-skipping) and zone-based BTM services created the most satisfying results. Due to the extra transfer (and extra waiting time), the Express and Trunk-Feeder services scored poor with the experienced travel time compared to the alternatives with a traditional transit service outline.

In the Mobili-City scenario, the differences between the bicycle catchment radius of 1000 m and asymmetric (1000-2000 m) were small. However, the application of the asymmetric catchment area created a much cheaper transit network. Therefore, applying an asymmetric bicycle catchment area for BTM stops should be applied. This also accounts for train stations, when the train trip distance is short. Furthermore, the applied BTM service should be traditional- or zone-based.

As final test, designs of multimodal networks with the bicycle as core were made for the case study USP. In the case study, the modal split, travel demand and traveller intensities were also incorporated. Two alternatives were made called Basic- and Plus alternative by using a self-made design strategy. In the Plus alternative, extra feeder stations were implemented to unburden Utrecht Centraal and the Uithoflijn. The simulation results showed a large improvement for the area. Both alternatives had a large decrease of car-users and an increase of multimodal trip travellers. Furthermore, the travel time of trips with the transit as main mode decreased a lot for most villages and neighbourhoods. With the Plus alternative, it was possible to relieve Utrecht Centraal and the Uithoflijn for a part of the route.

Based on the results and findings of the scenarios and the case study, it can be concluded that the applying a multimodal network with the bicycle as core creates a lower travel time for traveller when using a bicycle-transit mode combination compared to a walk-transit combination (Chapter 3) and for an existing area (Chapter 4). In the case study, the travel time for some zones was even almost halved. The case study also showed that applying a multimodal network with the bicycle core has an impact on the modal split. For trips to the USP, the number of car-users decreased with more than 1300 users (20 %) during the morning rush hours, while the number of (multimodal) transit users increased with around 2000 travellers (almost 10 %). About the operational costs, it is more tricky to draw conclusion. Chapter 3 showed that the operational costs are lower with a bicycle-transit combination compared to a walking-transit combination. During the case study, it was not possible to determine the difference in operational costs. It also largely depends on which BTM mode type is applied as a Bus/BRT has much lower costs than a tram or light rail. More study is needed to study the effects of a multimodal network with the bicycle as core on the operational costs.

Overall, this thesis has shown a lot of potential in applying a bicycle-transit mode combination at a large scale in a multimodal transit network. However, there were limitations and also assumptions were made during this thesis. Therefore, it is difficult to say how large the potential will be. A possible next step is to apply (temporarily) one BTM service line in an area based on the information and results in this thesis. Furthermore, a debate should be started about the necessity of having a BTM stop within walking range, which occurs in most cities. Instead, it should be changed to a BTM stop within cycling range.

Another finding of this thesis are the advantages of using an 'asymmetrical' bicycle catchment area. If a BTM stop is located in the opposite direction of the traveller's destination, the travellers have to make a detour. If the distance is more than 1000 m, it has a large negative impact on the travel time. It also makes the bicycle-transit combination slower than a walking-transit combination. Therefore, it is important to know in which general direction the destinations of the travellers are when applying a bicycle-BTM trip combination. For a bicycle-train combination, applying an asymmetric catchment area is less necessary as the travel speed and trip time in a train are much higher. Only if the train is used for low distances (<20 km) applying an asymmetrical catchment area is useful.

5.2 DISCUSSION

Over the course of this thesis, a lot of information, results, findings and limitations have passed by. For some of them, the choices and decisions can be debatable. One of the subjects in the literature study was the bicycle catchment radius. While a lot of studies examined the trip distance of cyclists, the results of these studies were very different. Multiple causes, from cultural differences to quality of the bicycle infrastructure can be the reason for this. Due to these causes, it was difficult to determine final bicycle travel distance willingness. Eventually, it was chosen to use relative low values. Main reason is to be sure that most travellers are willing to cycle these distances. But, it is possible that many travellers are willing to cycle much larger distances. The same issues are applicable for the trip preferences of the travellers, especially the mode preference can very different. Therefore, the eventual calculated experienced travel time values should be taken with some margin, the effects largely depends on which experienced travel time multipliers are changed.

In the Theoretical Application, simple scenarios were made with Excel and Visio as tools. With this approach, it was easy to make changes or add formulas into the calculations. The main disadvantages were the absence of travel demand and traveller intensities. Furthermore, the scenarios were schematic organised. Therefore, it can be questionable if these experiments were a good reflection of the outside world. For a part, this is certainly true. But when the results indicate a large difference between the alternatives, this substantiates the chosen approach and comparability with the outside world. Only when the differences are small, it is too premature to draw conclusions from it. Therefore, the results from the Theoretical Applications are valid to use.

As already described in sub-chapter 4.3, the VRU model had a lot of limitations. Main issues were its limitations when simulating multimodal trips and possibilities in making changes in the access and egress use of bicycles. Due to these limitations, not all findings could be implemented. Therefore, it is possible that simulations software available in the near future will create different simulation results.
Most of the information input, and simulation environment were based on occurrences in the Netherlands. Due to several reasons, extrapolating the thesis results into other countries is difficult. Firstly, the Dutch cycling culture is quite unique in the world, where almost everyone has one or more bicycles. Another important aspects are the climate and geography in the area. As the Netherlands is mostly flat with a mild climate, cycling is much more easy than in areas with hills and hot temperatures. In areas with these conditions, using a bicycle-transit combination might be very difficult or not even possible.
For designing a multimodal network with the bicycle as core, a design strategy was used. Parts were based on own statements and assumptions. Other strategies are likely possible. It is possible that using a different strategy would have created a different network design in the 'Mobili-City' scenario and case study. However, it is unlikely that it would have created a different conclusion.

5.2.1 Travellers with a disability

During this thesis, a lot of advantages about bicycle-transit trip combinations for the traveller were presented. However, not everyone is capable to use a bicycle. Approximately 6 % of the Dutch population (KiM, 2018) has a limited physical mobility. If the whole transit system is based on the bicycle as access and egress, they will most likely have large difficulty to use the transit system. This is of course a disadvantage which should not be ignored. However, applying a smaller catchment radius has a negative impact on the travel time and costs.
In a study of KiM (2019), it appeared that the current transit network is already insufficient for most travellers with a physical disability. Instead, they prefer to use the so-called "senior-taxi's". They function as a regular taxi, but have more facilities to help the person into the vehicle. Furthermore, they are accessible with a wheelchair. Therefore, it may be better to help these travellers in a different way. As this thesis indicate a lower operational costs in the designed multimodal networks, a part of these cost savings can be used to subsidise transportation for the travellers with physical disabilities. With subsidised vehicles or senior-taxi's, they can travel to the BTM stop and train stations. As there are much fewer BTM stops, it is easier to make all BTM stops more accessible for this traveller group. In the future, autonomous vehicles can be used to transport travellers with disabilities to the BTM stops and train stations.

5.3 Recommendation

This study showed the potential of designing the multimodal network with the bicycle as core. But there were also many uncertainties and assumptions. Furthermore, average conditions were often used. These factors have a high impact on the bicycle catchment radius values. Therefore, the stated catchment radius values in this study should not be seen as a hard limit, but more as an approximation. To limit the uncertainty range, more studies about bicycle catchment radius for BTM stops and train stations with different bicycle types are needed.
While a lot is known about the travel distance willingness and trip speed in the Netherlands of cyclists on regular bicycles, the information about E-bike and shared-bike users is limited. This information would be helpful to include the E-bike and shared-bike more into designing the multimodal network with the bicycle as core.
A large limitation of this thesis were the limits of simulating multimodal trips in the simulation software. To better simulate the effects of multimodal networks with the bicycle as core, software with more integration and program flexibility of multimodal trips is needed.
While travel time is one of, if not the, most important aspects to attract travellers for bicycle-transit trip combinations, it is not the only aspect. If the cycling roads are poor or unsafe, travellers are more

less willing to use a bicycle. It is also important to have storage facilities with enough capacity to store all those bicycles. Therefore, it is important to also take these the more “external” factors into account when designing BTM stops and train stations.

Sweco

The mobility department of Sweco has an increasing focus on bicycle projects like designing ‘bicycle fast-routes’ (snelfietsroutes). For these projects, it is useful to also take a look at nearby located BTM stops. When these bicycle fast-routes are connected to a BTM stop and this stop has enough bicycle parking facilities, it is for travellers much more attractive to use a bicycle-transit trip combination.
Also for projects focussing on improving the accessibility of an area, the results of the thesis are interesting. To improve the accessibility of an area, it can be effective to use fewer BTM stops instead of more. It is important that these BTM stops are easily accessible by bicycle and has proper facilities. Furthermore, the transit service lines at these stops should have a high frequency (>6 per hour) and a higher operational speed compared to the traditional bus service lines. These measurements can be made without high investment and operational costs. It is also important to take the general direction of the traveller’s destination into account and apply an asymmetrical catchment area (1000-2000 m).

Province of Utrecht

In sub-chapter 4.6, suggestions for the Province of Utrecht and its municipalities were presented. In short, the case study has shown that applying a multimodal network with the bicycle as core can be beneficial for the province. Especially for the more rural areas, the travel time for (multimodal) transit trips decreased significant. Furthermore, the car-use for trips to the USP decreased. Therefore, it can be interesting for the Province and municipalities to make bicycle-transit trip combinations more attractive.

6 REFERENCES

ANWB. (2018, December 27). *ANWB: 20 procent meer files op Nederlandse wegen*. Retrieved from ANWB: https://www.anwb.nl/verkeer/nieuws/nederland/2018/december/anwb-20-procent-meer-files-op-nederlandse-wegen

ANWB. (2019, Februari 11). *Wetgeving en regels voor elektrisch fietsen*. Retrieved from anwb.nl: https://www.anwb.nl/fietsen/elektrische-fietsen/wetgeving-en-regels/wetgeving-en-regels

Arentze, T. A., & Molin, E. J. (2013). *Travelers' preferences in multimodal networks: Design and results of a comprehensive series of choice experiments.* Elsevier.

Bach, B. (1999). Ontsluitingsstructuren. In V. de Groot, E. Kanters, & J. Korsmit, *Handboek Verkeers- en Vervoerskunde.* Den Haag: VUGA.

Bakker, P., van der Loop, H., & Savelberg, F. (2015). *Uitwisseling gebruikersgroepen 'auto-ov'.* Den Haag: KiM.

Bellinger. (1970). *Optimale Fahrpreise kommunaler und gemischtwirtschaftlicher Unternehmungen im Öffentlichen.* Berlin.

Bos, I., Van der Heijden, R., Molin, E., & Timmermans, H. (2004). The choice of park and ride facilities: an analysis using a context-dependent hierarchical choice experiment. *Environment and Planning A*, Volume 36, 1673-1686.

Bovy, P., & Hoogendoorn-Lanser, S. (2005). Modelling route choice behaviour in multi-modal transport networks. *Transportation*, 32: 341-368.

Brand, J., Hoogendoorn, S., van Oort, N., & Schalkwijk, B. (2017). Modelling multimodal transit networks: Integration of bus networks with walking and cycling. *2017 5th IEEE international conference on models and technologies for intelligent transportation systems (MT-ITS)*, (pp. 750-755).

Brogt. (2019). *De waaier van Brogt.* Deventer: Goudappel Coffeng.

Caulfield, B., O'Mahony, M., Brazil, W., & Weldon, P. (2017). Examining usage patterns of a bike-sharing scheme in a medium sized city. *Transportation Research part A: Policy and Practice*, Volume 100, 152-161.

de Bruijn, M., & de Vries, B. (2009). Het belang van kwaliteitsaspecten: uitdieping van het klantwensenonderzoek. *Oog voor de reiziger.* NS.

de Keizer, B., Kouwenhoven, M., & Hofker, F. (2015). New insights in resistance to interchange. *Transportation Research Precedia (8)*, 72-79.

Hoogendoorn-Lanser, S. (2005). *Modelling travel behaviour in multi-modal networks.* Delft: TRAIL Research School.

KiM. (2017). *Mobiliteitsbeeld 2017.* Den Haag: Ministerie van Infrastructuur en Waterstaat.

KiM. (2018). *De keuze van de reiziger.* Den Haag: Ministerie van Infrastructuur en Waterstaat.

KiM. (2018b). *Waar zouden we zijn zonder de fiets en de trein.* Den Haag: Ministerie van Infrastructuur en Waterstaat.

KiM. (2019). *De reizigers in het sociaal-recreatieve doelgroepenvervoer in Nederland.* Den Haag: Ministerie van Infrastructuur en Waterstaat.

Kouwenhoven, M., de Jong, G., Koster, P., van den Berg, V., Verhoef, E., Bates, J., & Warffemius, P. (2014). New values of time and reliability in passenger transport in The Netherlands. *Research in Transportation Economics*, volume 47, 37049.

Krygsman, S., Dijst, M., & Arentze, T. (2004). Multimodal public transport: an analysis of travel time elements and the interconnectivity ratio. *Transport policy*, 11(3), 265-275.

Ma, X., Yuan, Y., van Oort, N., Ji, Y., & Hoogendoorn, S. (2018). Understanding The Differnece In Travel Paterns Between Docked And Dockless Bike-Sharing systems: A Case Study In Nanjing, China. 19.

Milakis, D., Snelder, M., Van Arem, B., Van Wee, B., & De Almeida Correia, G. (2017). Development and transport implications of automated vehicles in the Netherlands: Scenarios for 2030 and 2050. *European Journal of Transport and Infrastructure Research*, 17(1), 63-85.

Rijsman. (2018). *Walking and bicycle catchment areas of tram stops in The Hague.* Delft.

Schakenbos, R., La Paix, L., Nijenstein, S., & Geurs, K. (2016). Valuation of a transfer in a multimodal public transport trip. *Transport Policy 46*, 72-81.

Shelat, S., Huisman, R., & van Oort, N. (2018). Analysing the trip and user characteristics of the combined bicycle and transit mode. *Research in Transportation Economics*, Volume 69, pages 68-76.

U Ned. (2018). *Programma U Ned; Voor bereikbare, gezonde groei in de Metropoolregio Utrecht.* Utrecht.

van der Loop, H., van der Waard, J., Haaijer, R., & Willigers, J. (2015, November 28). *Induced demand: new empirical findings and consequences for economic evaluation.* Den Haag: KiM.

van Nes, R. (2002). *Design of multimodal transport networks.* Delft: DUP Science.

van Nes, R., Hansen, I., & Winnips, C. (2014). *Potentie multimodaal vervoer in stedelijke regio's.* NWO.

Van Waes, A., Farla, J., Frenken, K., De Jong, J., & Raven, R. (2018). Business model innovation and socio-technical transitions. A new prospective framework with an application to bike sharing. *Journal of Cleaner Production 195*, 1300-1312.

Wardman, M. (2013). Value of Time Multipliers: A Review and Meta-Analysis of European-wide Evidence.

Wardman, M. (2014). Valuing convenience in public transport: Roundtable summary and conclusions. *International Transport Forum Discussion Paper, No. 2014-02* (p. 71). Paris: Organisation for Economic Co-operation and Development (OECD), International Transport Forum.

Wardman, M., Chintakayala, P., & de Jong, G. (2016). Values of travel time in Europe: Review and meta-analysis. *Transportation Research Part A: Policy and Practice*, Volume 92, 93-111.

Yap, M., Cats, O., & van Arem, B. (2018). Crowding valuation in urban tram and bus transportation based on smart card data. *Transportmetrica A: Transport Science*, DOI: 10.1080/23249935.2018.1537319.

APPENDIX

Ax 1 'Corridor' scenario total travel time results walking vs. cycling

Sub-Scenario	Total Travel Time						
	Walking (min)	Cycling (min)	Delta (min)	Delta (%)	Delta node (min)	# Nodes Faster	# Nodes Slower
Traditional 4x	3155	2794	360	11.4	4.9	67	6
Traditional 8x 1000 m	2885	2559	326	11.3	4.4	66	7
Traditional 8x 2000 m	2885	2587	297	10.3	4.0	59	14
Traditional 8x Asymmetric	2885	2518	367	12.7	5.0	69	4
Express 4x	2523	2351	171	6.8	2.3	48	25
Zone 4x	2375	2149	227	9.5	3.1	58	13
Trunk-Feeder 4x	2786	2359	427	15.3	5.8	61	12

Ax 2 'Corridor' scenario total experienced travel time results walking vs. cycling

Sub-Scenario	Total Experienced Travel Time						
	Walking (min)	Cycling (min)	Delta (min)	Delta (%)	Delta node (min)	# Nodes Faster	# Nodes Slower
Traditional 4x	4204	3498	706	16.8	9.5	69	4
Traditional 8x 1000 m	3731	3114	617	16.5	8.3	69	4
Traditional 8x 2000 m	3731	3066	665	17.8	9.0	66	7
Traditional 8x Asymmetric	3731	3023	709	19.0	9.6	70	3
Express 4x	3850	3200	650	16.9	8.8	56	17
Zone 4x	3269	2697	572	17.5	7.7	62	9
Trunk-Feeder 4x	4108	3142	966	23.5	13.1	65	8

Ax 3 'Corridor' scenario total travel time results cycling vs. cycling

Sub-Scenario	Total travel time				
	Delta tt (min)	Delta (%)	Delta node (min)	# Nodes Faster	# Nodes Slower
Traditional 8x 1000 m	236	8.4	3.2	66	0
Traditional 8x 2000 m	207	7.4	2.8	49	13
Traditional 8x Asymmetric	276	9.9	3.7	60	5
Express 4x	443	15.8	6.0	51	11
Zone 4x	645	23.1	8.7	57	5
Trunk-Feeder 4x	435	15.6	5.9	50	12

Ax 4 'Corridor' scenario total experienced travel time results cycling vs. cycling

Sub-Scenario	Total travel time exp				
	Delta tt (min)	Delta (%)	Delta node (min)	# Nodes Faster	# Nodes Slower
Traditional 8x 1000 m	384	11.0	5.2	62	4
Traditional 8x 2000 m	432	12.4	5.8	55	7
Traditional 8x Asymmetric	475	13.6	6.4	62	3
Express 4x	298	8.5	4.0	44	18
Zone 4x	801	22.9	10.8	58	4
Trunk-Feeder 4x	356	10.2	4.8	48	14

Ax 5 'Corridor' scenario total travel time sensitivity results walking vs. cycling

Sub-Scenario	Default min	Default %	BTM 30 & 50 min	BTM 30 & 50 %	BTM 40 & 67 min	BTM 40 & 67 %	Cycling 15 min	Cycling 15 %
Traditional 4x	4.9	11.4	4.8	12.4	4.6	14.1	5.4	12.7
Traditional 8x 1000 m	4.4	11.3	4.3	12.5	4.3	14.6	4.9	12.6
Traditional 8x 2000 m	4.0	10.3	3.9	11.3	3.8	12.9	4.9	12.4
Traditional 8x Asymmetric	5.0	12.7	4.7	13.7	4.5	15.4	5.6	14.5
Express 4x	2.3	6.8	2.3	7.6	2.5	9.2	3.0	8.8
Zone 4x	3.1	9.5	2.8	10.0	2.5	10.2	3.7	11.7
Trunk-Feeder 4x	5.8	15.3	5.3	15.6	4.8	16.2	6.5	17.1

Ax 6 'Corridor' scenario total experienced travel time sensitivity results walking vs. cycling

Sub-Scenario	Default min	Default %	BTM 30 & 50 min	BTM 30 & 50 %	BTM 40 & 67 min	BTM 40 & 67 %	Cycling 15 min	Cycling 15 %
Traditional 4x	9.5	16.8	9.4	18.2	9.2	20.5	10.0	17.5
Traditional 8x 1000 m	8.3	16.5	8.3	18.3	8.1	20.9	9.1	18.0
Traditional 8x 2000 m	9.0	17.8	8.7	19.3	8.6	22.2	9.6	19.1
Traditional 8x Asymmetric	9.6	19.0	9.3	20.6	9.0	23.3	10.2	20.2
Express 4x	8.8	16.9	8.5	17.8	8.7	19.9	9.3	17.9
Zone 4x	7.7	17.5	7.2	18.0	6.8	19.3	8.2	18.7
Trunk-Feeder 4x	13.1	23.5	12.2	23.9	11.6	25.3	13.6	24.4

Ax 7 'Corridor' scenario sensitivity number of nodes faster or slower travel time compared to walking-transit equivalent

Sub-Scenario	Default Faster	Default Slower	BTM 30 & 50 Faster	BTM 30 & 50 Slower	BTM 40 & 67 Faster	BTM 40 & 67 Slower	Cycling 15 Faster	Cycling 15 Slower
Traditional 4x	67	6	66	7	67	6	68	5
Traditional 8x 1000 m	66	7	64	9	65	8	68	5
Traditional 8x 2000 m	59	14	59	14	58	15	62	11
Traditional 8x Asymmetric	69	4	65	8	65	8	70	3
Express 4x	48	25	49	24	50	23	52	21
Zone 4x	58	13	55	16	55	16	58	13
Trunk-Feeder 4x	61	12	61	12	60	13	61	12

Ax 8 'Corridor' scenario number sensitivity of nodes faster or slower experienced travel time compared to walking-transit equivalent

Sub-Scenario	Default Faster	Default Slower	BTM 30 & 50 Faster	BTM 30 & 50 Slower	BTM 40 & 67 Faster	BTM 40 & 67 Slower	Cycling 15 Faster	Cycling 15 Slower
Traditional 4x	69	4	69	3	70	3	70	3
Traditional 8x 1000 m	69	4	69	3	70	3	70	3
Traditional 8x 2000 m	66	7	66	2	71	2	71	2
Traditional 8x Asymmetric	70	3	70	3	69	4	71	2
Express 4x	56	17	56	17	56	17	57	16
Zone 4x	62	9	62	9	60	11	66	4
Trunk-Feeder 4x	65	8	66	7	66	7	67	6

Ax 9 'Corridor' Scenario sensitivity connection quality walking vs. cycling

Sub-Scenario	Default min/km	Default %	BTM 30 & 50 min/km	BTM 30 & 50 %	BTM 40 & 67 min/km	BTM 40 & 67 %	Cycling 15 min/km	Cycling 15 %
Traditional 4x	1.2	23.9	1.1	24.8	1.1	26.0	1.4	27.0
Traditional 8x 1000 m	0.9	20.0	0.8	21.1	0.8	22.8	1.0	23.2
Traditional 8x 2000 m	0.8	18.6	0.7	19.0	0.7	19.8	1.0	22.8
Traditional 8x Asymmetric	0.9	21.0	0.9	21.7	0.8	22.7	1.1	24.6
Express 4x	1.0	23.6	1.0	24.6	1.0	26.2	1.2	27.4
Zone 4x	1.1	25.4	1.0	25.9	0.9	26.5	1.3	29.3
Trunk-Feeder 4x	1.3	26.7	1.2	27.1	1.1	27.8	1.4	30.3

Ax 10 'Corridor' Scenario sensitivity experienced connection quality walking vs. cycling

Sub-Scenario	Default min/km	Default %	BTM 30 & 50 min/km	BTM 30 & 50 %	BTM 40 & 67 min/km	BTM 40 & 67 %	Cycling 15 min/km	Cycling 15 %
Traditional 4x	2.6	37.0	2.6	38.6	2.5	41.0	2.8	38.6
Traditional 8x 1000 m	1.9	32.0	1.9	33.9	1.8	36.3	2.2	36.0
Traditional 8x 2000 m	2.1	34.4	2.0	35.5	1.9	38.2	2.2	36.7
Traditional 8x Asymmetric	2.1	34.5	2.0	36.2	1.9	38.8	2.2	37.0
Express 4x	2.9	40.6	2.7	40.9	2.7	43.1	3.0	42.4
Zone 4x	2.5	40.6	2.4	40.6	2.3	42.3	2.7	42.6
Trunk-Feeder 4x	2.9	40.9	2.7	40.8	2.6	42.4	3.0	42.7

Ax 11 'Corridor' Scenario sensitivity connection quality cycling vs. cycling

Sub-Scenario	Default min/km	Default %	BTM 30 & 50 min/km	BTM 30 & 50 %	BTM 40 & 67 min/km	BTM 40 & 67 %	Cycling 15 min/km	Cycling 15 %
Traditional 8x 1000 m	0.33	8.8	0.35	10.2	0.38	12.4	0.32	8.7
Traditional 8x 2000 m	0.27	7.1	0.27	7.8	0.28	9.1	0.30	8.2
Traditional 8x Asymmetric	0.38	9.9	0.38	10.9	0.38	12.4	0.38	10.4
Express 4x	0.42	11.1	0.36	10.4	0.25	8.2	0.44	12.0
Zone 4x	0.61	16.0	0.55	15.8	0.44	14.4	0.62	17.1
Trunk-Feeder 4x	0.34	9.1	0.29	8.5	0.21	6.9	0.36	9.9

Ax 12 'Corridor' Scenario sensitivity experienced connection quality cycling vs. cycling

Sub-Scenario	Default min/km	Default %	BTM 30 & 50 min/km	BTM 30 & 50 %	BTM 40 & 67 min/km	BTM 40 & 67 %	Cycling 15 min/km	Cycling 15 %
Traditional 8x 1000 m	0.43	9.6	0.45	11.1	0.45	12.7	0.56	12.7
Traditional 8x 2000 m	0.57	12.8	0.54	13.2	0.55	15.2	0.59	13.6
Traditional 8x Asymmetric	0.58	12.9	0.58	14.1	0.58	16.1	0.62	14.1
Express 4x	0.31	6.8	0.14	3.5	0.01	0.2	0.32	7.3
Zone 4x	0.77	17.1	0.60	14.8	0.47	13.1	0.78	17.8
Trunk-Feeder 4x	0.30	6.6	0.14	3.5	0.04	1.2	0.31	7.0

Ax 13 '2D Corridor' scenario sensitivity connection quality

Alternative	Default min/km	Default %	BTM 30 & 50 min/km	BTM 30 & 50 %	BTM 40 & 67 min/km	BTM 40 & 67 %	Cycling 15 min/km	Cycling 15 %	10 Vehicles min/km	10 Vehicles %
Walking	4.3	-8.9	3.9	-7.7	3.5	-6.0	4.3	-12.6	5.4	-29.1
Cycling 1k	3.9	-	3.6	-	3.2	-	3.8	-	4.1	-
Cycling 2k	4.7	-16.6	4.3	-16.9	3.9	-17.4	4.5	-15.6	4.3	-3.6
Cycling 2k 2 lines	4.7	-15.9	4.3	-15.9	3.8	-15.9	4.4	-15.0	4.9	-17.4
Cycling Asymmetric	3.8	1.7	3.6	0.9	3.2	-0.3	3.7	2.4	4.0	1.8

Ax 14 '2D Corridor' scenario sensitivity experienced connection quality

Alternative	Default min/km	Default %	BTM 30 & 50 min/km	BTM 30 & 50 %	BTM 40 & 67 min/km	BTM 40 & 67 %	Cycling 15 min/km	Cycling 15 %	10 Vehicles min/km	10 Vehicles %
Walking	7.2	-17.6	6.7	-17.1	6.1	-16.2	7.2	-19.8	9.0	-39.1
Cycling 1k	6.1	-	5.7	-	5.3	-	6.0	-	6.5	-
Cycling 2k	6.8	-11.9	6.4	-11.8	5.9	-11.6	6.6	-11.1	6.1	5.6
Cycling 2k 2 lines	6.8	-10.9	6.3	-10.5	5.8	-9.8	6.6	-10.2	7.1	-10.3
Cycling Asymmetric	5.9	3.0	5.6	2.4	5.2	1.5	5.8	3.5	6.3	2.9