Bikeability in Nijmegen

A mixed method case study combining measured and perceived bikeability through a geospatial index

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Summary

A growing majority of the global population is already living in cities, with no sign of urbanisation slowing down. Together with the challenges and consequences associated with climate change, urban mobility is under pressure. The amount of space in increasingly dense cities is limited and the emission of greenhouse gases needs to decrease rapidly. One of the most simple, yet versatile modes of transport is cycling and it is part of a more sustainable urban future. The influence of the physical environment on cycling is undeniable. In order to better understand this influence, bikeability is a key concept. The Netherlands already is a leading country in terms of cycling mobility, thus much can be learned from the Dutch urban context. The aim of this research is to gain insight into a city's bikeability, adapted to the perceptions of inhabitants. To achieve this goal, the following research question has been formulated: "*How do the inhabitants of two neighbourhoods in Nijmegen perceive the bikeability in their city and how can this information be applied on a standard bikeability index, creating a more accurate, revised index in the process?".* In preparation of the research, relevant theories and frameworks on cycling and the physical environment have been explored to develop a conceptual model. The main research method concerns a special bikeability index derived from the literature, which is applied on the case of Nijmegen. With this index, the bikeability in a certain area is measured and visualized by analysing public geospatial data, which serves as the main data input. First, an objective version of the bikeability has been analysed. Then, context-specific, subjective data was gathered by conducting a survey in two neighbourhoods in Nijmegen. This makes this thesis a mixed-methods case study design.

The first analysis included four indicators of the physical environment, being quality of cycling infrastructure, connectivity, destination accessibility and elevation difference. These were analysed separately and merged into one image depicting the bikeability scores on a 1 to 10 (worst to best) scale. This image shows high scores of bikeability in and around the city centre, but these scores slowly decrease while moving towards the city's borders. The difference between the centre and suburbs is predominantly caused by variations in destination density and connectivity. The case study neighbourhoods, Wolfskuil and Nije Veld, both have relatively high average scores (6,01 and 6,27 as opposed to 5,13 for the whole city) due to their central location within the city. The survey (N = 52) shed a somewhat different light on the actual bikeability in Nijmegen. The bikeability indicators were perceived different between city and neighbourhood and the importance of the indicators differed significantly.

Extra qualitative input from the survey regarding the disadvantages of junctions provided new insight and led to this being added to the index as an extra indicator. Another change concerned the doubled weight of destination accessibility and cycling facilities, as these factors were found to be far more important than the other two. Besides this, destination accessibility was rescaled to prevent disproportional low values in suburbs and some destinations were applied a higher weight. These changes have been used to compose a revised bikeability index, that shows a more accurate and truthful image of the bikeability in Nijmegen and the two neighbourhoods. The most remarkable change is the shifted balance, as bikeability scores in suburbs have risen significantly, while some inner city neighbourhoods have slightly lower scores, making the overall difference in the city smaller. Large junctions that are bad for cycling progress have a clear impact on bikeability as well. Based on these results, the standard bikeability index is a good foundation for measuring bikeability, but it needs contextual input from a city to be as accurate as possible.

Preface

Hereby, I present to you my Master's thesis as conclusion of the Spatial Planning degree. A study in the field of cycling mobility, that represents the progress I've made as a spatial planner and academic during the Master as well as the Bachelor program at the Radboud University in Nijmegen. Within the specialisation of Urban and Regional Mobility, it was mobility through cycling that inspired me most to write my thesis about. The unforeseen Covid-19 pandemic made the last part of my life as a student different than I had imagined beforehand. It also had its impact on the choices I had to make surrounding the thesis, such as the decision to not combine it with an internship. Many potential hours of writing and studying on campus were eventually carried out in the working environment that is my own room. The inevitable distractions and difficulties I experienced resulted in a lengthier process than I aimed for.

Nonetheless, it has been an educative and insightful period. I had little experience in advance with most of the theories and methodologies I've used to conduct this study. Doing research with Geographical Information Systems and SPSS was new to me and often challenging, but when it worked out well, it was also very fulfilling. I couldn't have done this without the guidance of my supervisor. Therefore, I would like to thank Kevin Raaphorst for his continuous support and all valuable feedback throughout the entire process. He was always available for a meeting on short notice whenever I ran into a seemingly unsolvable problem. Finally, I would like to thank my friends, my family and my girlfriend in particular, who have supported me when I needed it most during this period.

Lucas Bijl
Nijmegen, February 2022

Table of Contents

List of Abbreviations

Abbreviation	Meaning	English translation
AHN	Actueel Hoogtebestand Nederland	General elevation database of the Netherlands
BAG	Basisregistratie Adressen & Gebouwen	Registration of addresses and buildings
CBS	Centraal Bureau voor de Statistiek	Central institute for statistics
CS-MM	Case Study – Mixed Methods design	
EU	European Union	
GIS	Geographical Information System	
NAP	Normaal Amsterdams Peil	Standard measure for ground level
NWB	Nationaal Wegen Bestand	National road database
OSM	Open Street Map	
PASTA	Physical Activity through Sustainable Transport Approaches	
PDOK	Publieke Dienstverlening Op de Kaart	Public service for geospatial data
SES	Sociaal economische status	Social-economic status

1. Introduction

1.1 Problem statement and context

Mobility is one of the most important pillars of modern day society. Many daily activities require us to be mobile in some sort of way; going to work, doing groceries, bringing the kids to school, visiting friends, and so on. In cities, urban mobility is essential for the functionality of the city. Over the past decades, the distance each person covers per year has steadily increased and it is expected that this will keep rising in the years to come. Together with the ongoing trend of urbanisation, the number of movements in cities will increase as a consequence. This development also applies on the Netherlands, where the distance travelled by the whole population increased from 193,6 billion kilometres in 2010 to 211,9 billion in 2019. These figures include all common modes of transport on the ground. Of those kilometres, almost 70% was done by car. In the last ten years, the number of motorized vehicles on the road has increased from 10,5 to 11,9 million. Moreover, the average travelled kilometres per vehicle has risen from 141 thousand in 2010, to 152 thousand in 2019 (Centraal Bureau voor de Statistiek, 2022).

Unfortunately, the increased level of mobility has negative consequences for the environment. The mobility sector is responsible for 22,5% of the total CO_2 emissions in the Netherlands in 2019 (Rijksoverheid, 2021). 37% of those emissions can be attributed to car traffic (CROW, 2021). To counter climate change, the members of the European Union have agreed that the EU has to reduce its greenhouse gas emissions with 55% by 2030, and to become climate neutral by 2050 (Europese Commissie, 2020). An increase of motorized traffic is at odds with reducing CO_2 emissions. In order to meet the climate goals set by the European Union (EU), the mobility sector has to change substantially. Besides contributing to global warming, the greenhouse gases emitted by motorized transport create air pollution on a local scale as well.

Reducing the environmental footprint of mobility requires a shift to more sustainable modes of transport. The concept of sustainable mobility is often associated with technological innovation and new forms of transportation. Cars powered by electricity or hydrogen, buses on green gas and mobility as a service are a few examples of how technology can be applied to make mobility more sustainable. Even though these are part of the solution, sustainable mobility is not entirely dependent on technological innovations. The simplest, most versatile modes of sustainable transport fall under active mobility. Active mobility includes walking, cycling and other modes of transportation that require energy generated by physical activity. There are several benefits associated with active mobility, as opposed to motorized mobility. First of all, active mobility doesn't produce any harmful emissions, as opposed to other motorized modes of transport. Active mobility is also beneficial on a local scale, as it doesn't create air pollution in cities and thus contributes to a cleaner and healthier environment. Besides the environmental advantages, walking and cycling are beneficial to physical and mental health. Making short distance trips on foot or by bike contributes to a healthier lifestyle, and thus lowers the risk of diseases associated with movement poverty, such as obesity (Koszowski et al., 2019).

In terms of urban planning, active forms of mobility only require a minimum amount of public space compared to motorized transport modes. When stationary, a person on foot only makes use of 0,3 m2, a person on a bus uses 1 m2, a cyclist 1,5 m2, while a car uses up to 10m2. The amount of required space multiplies when the transport mode is in motion (Sanchez, 2018). The urban population will continue to rise, which will make cities even more crowded than they already are at the moment. If the popularity and share of walking and cycling in urban mobility doesn't increase, this will result in more cars on the road, more congestion, more pollution, and less public space to live in. Even though active urban mobility comes with many advantages, it is still underrepresented in daily mobility. This is the consequence of decades of car-centred mobility planning. Even in the Netherlands, which is known for its famous cycling culture, the car is overly represented in urban areas and many cities partly rely on car-centred mobility and accompanying infrastructure. Because of this, people are more dependent on their car in order to have a high level of mobility.

The share of cycling in Dutch national mobility has been substantial for decades; over a quarter of all journeys are made by bike. The bike is mostly used during free time and for leisure purposes, followed by commuting trips and trips to and from school (Kennisinstituut voor mobiliteitsbeleid, 2019). Even though the bicycle is a much more common transport mode than in most European countries, the total number of trips made and distance covered by bike has practically remained the same over the last decades (Centraal Bureau voor de Statistiek, 2020; Van der Bijl, 2018). For instance, the total covered distance by bike has risen by 4% since 2010 to a total of 15,3 billion kilometres, which is not much, given the rise of the e-bike in the last decade and expansion and improvement of cycling infrastructure (Kennisinstituut voor mobiliteitsbeleid, 2019). In several cities however, the already large share of cycling has increased more significantly over the last ten years. This includes Amsterdam, which is regarded as one of the world's cycling capitals. The other three big cities are also included, as well as some smaller cities. In Nijmegen, for example, the share of the bicycle in the total number of journeys has increased from 34% in 2010 to 44% in 2019 (De Haas & Hamersma, 2020).

Despite the positive development of the bicycle as transport mode and active mobility as a whole, there is still room for improvement. Looking more closely at the city of Nijmegen, the share of cycling for short trips (<7,5 kilometres) to, from and within the city is 40,1%. The share of walking is 25%, while the share of the car is 30% for this type of journey. For longer distance trips, the share of the bicycle decreases and the share of the car increases. With the emergence of the e-bike last decade, there could be a lot of growth potential for the bicycle for longer journeys. The municipality does have the ambition to further expand the share of active mobility and cycling in particular (Gemeente Nijmegen, 2019). Active mobility, sometimes in combination with public transport, offers a good alternative to car travel.

Hence, a *modal shift* needs to take place, where car users stop using the car for short trips and use the bicycle instead. In order to achieve this modal shift, a change in travel behaviour needs to be brought about. There are several different factors that influence travel behaviour. Among these are general characteristics, like age and gender, and social-cultural characteristics, like income, education, ethnicity and so forth. Besides these, there are factors like climate and weather. Such characteristics are hard or impossible to influence through a municipality's policy. Therefore, mobility policy has to be focused on factors of travel behaviour that can be changed. One of the most important determinants of cycling behaviour is the built environment. This predominantly includes, amongst other factors, a city's spatial structure and infrastructure (Götschi et al., 2017). For a well targeted policy, insight into the problems and opportunities surrounding these factors is essential. Therefore, this study aims to provide the required insight into the spatial structure of Nijmegen by mapping its *'bikeability'*. For this purpose, a *bikeability index* that consists of different spatial components is utilized.

1.2 Research aim and questions

This research intends to contribute to the field of knowledge of cycling in urban planning. To be more specific, this thesis aims to gain insight into the bikeability of an urban area, adapted to the perception of inhabitants who potentially use the bicycle for travelling within the city. New and specific knowledge in this field can contribute to more effective policy making for cycling in neighbourhoods where cycling is lacking behind as a mode of transport. Besides this, the acquired knowledge can be used to improve the existing bikeability index.

Following the research objective, the main question of this research is formulated:

How do the inhabitants of two neighbourhoods in Nijmegen perceive the bikeability in their city and how can this information be applied on a standard bikeability index, creating a more accurate, revised index in the process?

In order to answer the main question of the research, it is divided into three sub-questions:

1. *How bikeable are the neighbourhoods in the case study compared to the city as a whole, according to a bikeability index using objective indicators?*

The first sub-question is focused on applying an existing bikeability index on the case study that is done in this research. The case study consists of two neighbourhoods in the city of Nijmegen, the first being Wolfskuil and the second being Nije Veld. The choice for these particular neighbourhoods is further explained in chapter 3, in which the neighbourhoods are thoroughly discussed as well. The existing bikeability index is discussed in chapter 2, and some relevant indicators based on literature are added to the index. The factors that bikeability is comprised of are mostly about the physical environment.

2. *How do inhabitants rate the bikeability in Nijmegen compared to their own neighbourhood, and which elements of the physical environment are of importance to them?*

The second sub-question is aimed at finding a more qualitative meaning of bikeability of an urban area. In order to determine the bikeability, inhabitants of different social-economic classes are interviewed on their perception of the concept, while maintaining a focus on the physical environment. The group of inhabitants of the neighbourhoods that is most important, is the group with a low social-economic status, because cycling is underrepresented as transport mode among this group.

3. *To what extent do the results of the survey relate to the results of the first sub-question and how can these be combined to determine the actual bikeability?*

The last sub-question is focused on comparing the results of the first two sub-questions. The results of the first question are of quantitative nature, while the results of the second question are mostly of qualitative nature. The purpose of this question is to find out what the balanced bikeability of a neighbourhood looks like. This actual bikeability seeks to combine the most relevant objective indicators and the most important perceived indicators of the physical environment. Answering this question will also give insight into the effectiveness of the bikeability index that is used and its relevance for the Dutch urban context.

1.3 Relevance

The relevance of the research has already come to pass to some extent in the problem statement. In this paragraph the relevance will be further elaborated on, as a distinction is made between the scientific and societal relevance of the research.

1.3.1 Scientific relevance

The concept of bikeability is relatively new within the existing literature on cycling. Its walking counterpart, walkability, has been studied more extensively throughout American as well as European cities. Walkability is a more common mode of transport in most cities around the world, and has therefore received greater attention in research. The existing cycling culture in the Netherlands however, makes bikeability an interesting concept to research in its cities. Although cycling is very popular in the Netherlands, very few research has been done into the bikeability of cities. This is possibly due to the assumption that Dutch cities already are very bikeable, and that the concept therefore doesn't require further research. Mapping the bikeability of an urban area or neighbourhood in the Netherlands can provide new insight into the research field of cycling.

Existing research into bikeability of cities has been predominantly focused on North American cities and some other non-European cities. The bikeability index, developed by Winters et al. (2013), functions as a guiding framework in the theory of this research and has been tested and developed in the city of Vancouver, Canada. There are major differences between North American cities, like Vancouver, and Dutch cities. The most prominent difference, amongst others, is the spatial structure. Dutch cities are generally more compact and more densely populated, while North American cities often have to cope with the effects of urban sprawl (Tan et al., 2013). The bikeability of a city is strongly dependent on the city's spatial structure, which means testing the concept on compact Dutch cities can provide interesting results and new insight. However, using an index developed in a vastly different urban context and applying it on the Dutch urban context in the same way, isn't certain to result in the best representation of bikeability in the case of Dutch cities.

In order to increase the reliability and the scientific relevance of the research, the bikeability is also determined by people's perceptions. By involving the perceived physical environment, the research receives a qualitative impulse. A significant amount of research has been conducted on the perceived environment in combination with cycling behaviour, yet few research is linked to bikeability. Most research concerning bikeability uses objective indicators to measure how suitable a certain area is for cycling, so the research can rely on existing spatial data (Ma & Dill, 2017). This research aims to find the difference between bikeability according to objective, generally applicable indicators and the perceived bikeability according to inhabitants.

1.3.2 Societal relevance

Sustainable mobility is becoming an increasingly more important theme on the political and societal agenda of cities. In order for cities to reach the climate goals in the coming decades, CO_2 emissions have to be strongly reduced. Mobility is one of the larger contributors to these emissions in cities and creates other harmful pollutions on a local scale as well, which is bad for air quality and the health of people in general. A shift to more active mobility is an evident solution to these problems and to the challenge that is climate change (Koszowski et al., 2019). Besides this, active mobility offers a solution to the scarcity of public space in cities. Growing urban populations cause more traffic in cities, which means more cars and more car infrastructure, if urban mobility stays business as usual (Sanchez, 2018). Also on an individual level cycling comes with benefits, as it is a form of exercise and good for health. More specifically, cycling regularly lowers the risk of diseases like cancer and obesity, plus a lower mortality rate in general (Oja et al., 2011). Another benefit of more bicycles and less cars on the streets is the attractivity of an area or neighbourhood, as a street becomes more pleasant and safe to live and be in (Gehl, 2013). Even in a cycling nation like the Netherlands, a large part of urban mobility is unsustainable, so there's still ground to be gained for cycling.

Taking these benefits into account, it comes as no surprise that governmental bodies are committing to cycling in their mobility policies. Improving cycling infrastructure is essential for more cycling, but in order for this to be the most effective, detailed knowledge about increasing the use of the bicycle is necessary. Mapping bikeability in cities is a powerful visual tool, certainly when it is tailored to the and needs of cyclists in the area and the inhabitants. Determining the bikeability for a certain neighbourhood can lead to different suitable measures and interventions than in other neighbourhoods with other characteristics. Inhabitants may have other requirements for good bikeability of their neighbourhood than inhabitants in another neighbourhood have. A tailored approach for improving the perception bikeability in an area benefits the (potential) cyclists in this area. For the inhabitants that are not accustomed to cycling a change in travel behaviour is needed, on top of spatial interventions. If this group is not willing to use the bicycle and change their travel behaviour at all, then spatial interventions aimed at this group are of no use (Liang Ma & Cao, 2019). This research can therefore be relevant for policy makers by providing detailed information about what policy could improve bikeability and what policy isn't effective.

1.4 Research design

The following part of this thesis concerns the theoretical framework in chapter two. Literature on relevant concepts and theories are part of the structure in this deductive research and are discussed here. In chapter three, the strategy and research methods are explained, going into further detail of how the research is actually carried out. Chapter four contains a detailed description of the chosen case study. In chapter five the results are presented and chapter six will cover the conclusion and discussion. Finally, recommendations are made and the research is reflected on in a critical manner.

2. Theoretical framework

In this chapter, the concepts and theories central in this thesis are presented and explained. The first part of the chapter covers a systematic literature review explaining the determinants of cycling behaviour. This chapter is subdivided in physical environment factors, containing built and natural environment and trip characteristics, and individual aspects. The latter is split up in population characteristics, such as the socio-economic status (SES) and demography, and in perception of environment, which is a psychological aspect to cycling. After the analysis of the relevant aspects that explain cycling behaviour, the bikeability index is introduced. The choice for this index and theory is clarified and its applicability on the research is explained. The indicators that are used in this index stem from the most relevant physical environment factors for cycling, according to the literature. The feasibility of measuring the indicators is taken into account as well, so some relevant aspects in literature are adjusted or left out. Finally, a conceptual framework of the research is illustrated, giving a visual presentation of the research.

2.1 Determinants of cycling behaviour

The choice for cycling as transport mode can be composed of many factors and determinants, some more important than others. In this research, the focus is mostly on the determinants that belong to the built or physical environment. This includes, among other factors, the spatial structure of a neighbourhood and the physical properties of a specific cycling route. In order to specify what determines cycling in general, a broad framework about cycling factors provides clarity and serves as a good starting point. The Physical Activity through Sustainable Transport Approaches (PASTA) framework, developed by Götschi, Nazelle, Brand & Gerike (2017), is a comprehensive conceptual framework of active travel behaviour.

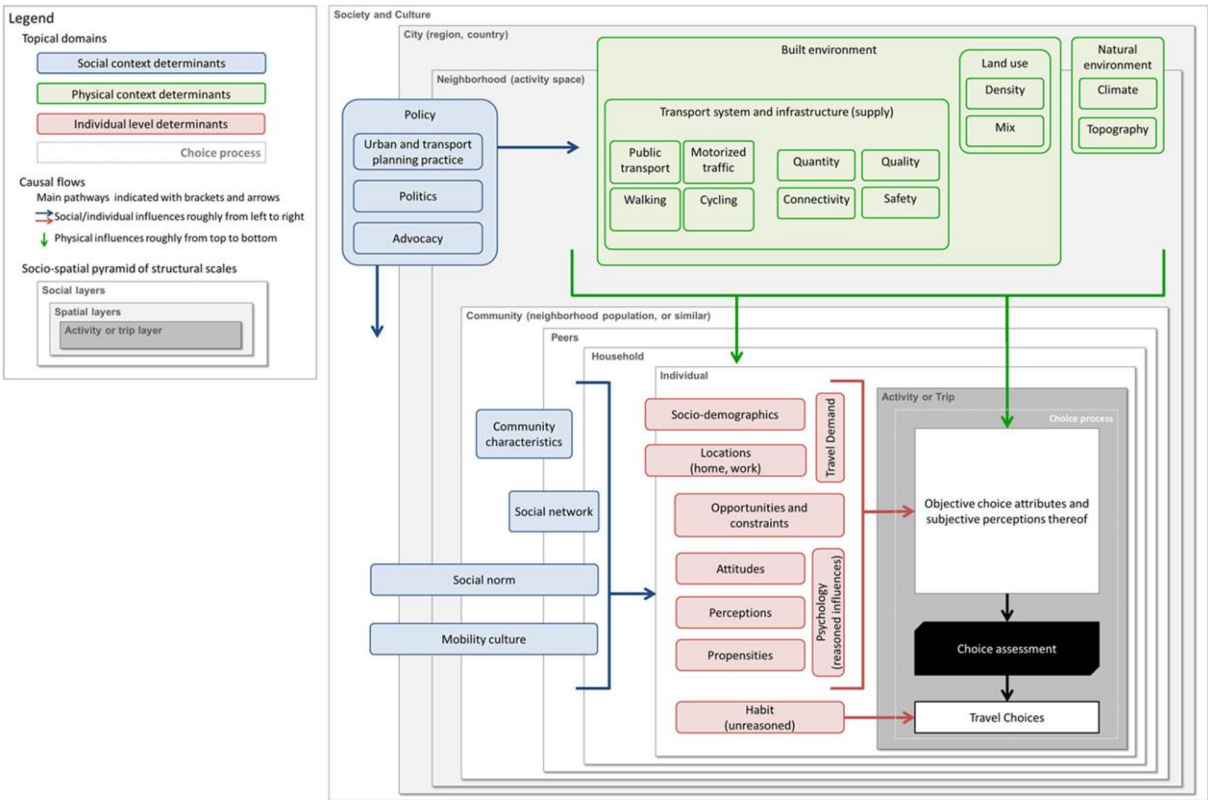

Figure 2.1: The PASTA framework (Götschi et al., 2017)

It includes the most important factors that were found after reviewing numerous other frameworks. The resulting framework is depicted in Figure 2.1.

The PASTA framework distinguishes three topical domains of influence on cycling behaviour: social context determinants, physical context determinants and individual level determinants. The literature review will foremost focus on the physical context determinants, outlined in green in Figure 2.1. Throughout the research, the bikeability is composed of indicators that are derived from the factors in this domain. Within the green outline, some factors will turn out to be more important than others while developing the conceptual framework for this thesis. For example, climate factors aren't included as these do not belong to the built environment. Also, the other three transport systems are kept on the side line, as this thesis has a special focus on bikeability. The physical context isn't the only domain that is relevant for this research. To make statements about the bikeability in a neighbourhood as it is perceived by a specific population group, information about the characteristics and their influence on (active) travel behaviour for this group can be helpful. This implies involving some of the factors in the blue and red outlines as well, respectively the social context determinants and the individual level determinants.

While the PASTA-framework is very comprehensive, it is also quite complex. Not every aspect presented in the framework is relevant for this thesis and there is no focus on cycling specifically. Therefore, a less complicated framework might be more practical for shaping the theoretical framework. Marquart, Schlink & Ueberham (2020) have designed such a framework, which can be seen in the image below. It is a simplified version of the framework designed by Gotschi et al. (2017) and it is focused solely on cycling for transport. The first part of the theoretical framework follows the structure of the model, continuing initially with the physical environment and its three components. Trip characteristics and the natural environment play smaller parts compared to the built environment. This is followed up by a paragraph on the influence of the physical environment on cycling, and on cycling in the Netherlands specifically. An extra paragraph is dedicated to the individual aspects of cycling, in which perception plays a significant role.

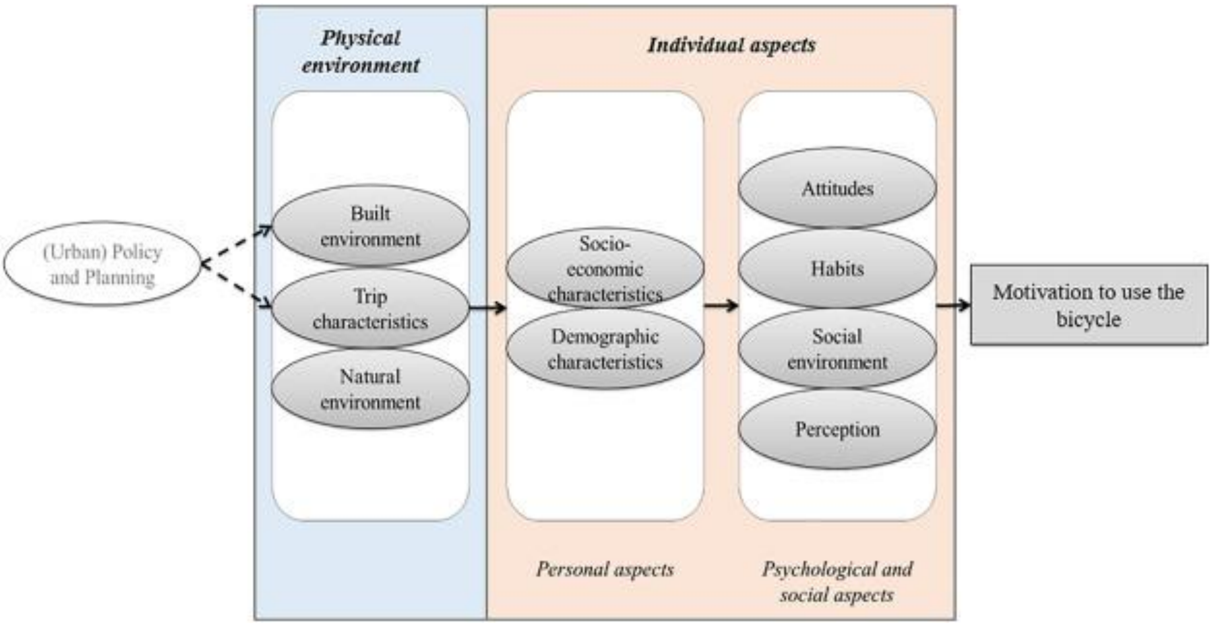

Figure 2.2: Simplified model based on the framework of Götschi et al. (2017), adjusted for cycling. (Marquart et al., 2020)

2.2 Physical environment

The physical environment can be divided in three components; the built environment, trip characteristics and the natural environment. The built and physical environment are somewhat interchangeable, as a lot of physical elements in the urban context are manmade and thus considered 'built'. However, it is valuable to identify aspects that belong to trip characteristics and the natural environment. When it comes to stimulating active mobility, the built environment and the trip characteristics can be influenced by policy and planning. The natural environment can't be changed by human interference without it becoming 'built'. Trip characteristics can only be affected by changing the built environment, so mobility planning doesn't influence these directly (Marquart et al., 2020).

2.2.1 Built environment

There is an extensive amount of research available on the built environment of cities, and a considerable part is about the connection between the built environment and travel behaviour. To establish this connection, it is necessary to define *built environment.* Lawrence and Low (1990) describe it as an abstract concept, in which any natural environment is changed through human construction. So any interference by humans in any environment, essentially transforms it to built environment. The built environment consists of built forms, that vary from buildings to parks and streets. In order to make this concept more tangible and easier to work with, the definition given by Hassler and Kohler (2014) is more suitable given the nature of this research: "The built environment includes manmade building and infrastructure stocks that constitute the physical, natural, economic, social and cultural capital" (p. 120).

There is no doubt that travel behaviour of people is influenced and partially determined by the built (or physical) environment. However, there is no general consensus yet on how this correlation precisely works. A numerous amount of research has attempted to find and explain the effects of various built environment factors and characteristics on travel behaviour. In these studies, a lot of variation exists in geographical scale, the found and chosen characteristics and the transport mode. What stands out, is that the majority of research on active travel combined with the built environment relies on data gathered specifically on a certain national- or urban level. The results of this case-specific type of research are difficult to generalize and to compare with each other, due to different spatial settings, research methods and variables (Christiansen et al., 2016). According to Handy et al. (2002), research efforts within the field of urban planning have looked into possibilities of land use and design policies for increasing active forms of transport, among which cycling and walking are the most important. Walking has been a more researched subject than cycling in urban planning literature, as it is more common and adopted than cycling in most countries (Pikora et al., 2003).

Density, Diversity and Design

The precise effects of different variables of the built environment are not so evident, because research results are divided for this matter. Yet there are some important studies that have been leading in this field of research. Cervero and Kockelman (1997) have conducted a study in which travel demand is influenced by three major dimensions: density, diversity and design, named the 3D's together. The effect of density on travel demand already was well-known before, but in this study it was incorporated in one theory with the other two dimensions for the first time. The dimension of density includes characteristics like population density, employment rates, and accessibility to jobs. Diversity includes characteristics like the dissimilarity of land use, number of different amenities in an area, and proximity of residential locations to other amenities. Lastly, design includes several characteristics of infrastructure for cars, cyclists and pedestrians (Cervero & Kockelman, 1997). In their meta-analysis, Ewing and Cervero (2010) conducted an analysis of the built environment literature that involves travel behaviour. The study found that there are two other significantly important dimensions of the built environment that affect travel demand. These fourth and fifth 'D's' are destination accessibility and distance to transit. These have some overlap with density and diversity, but were found significant enough to be added as extra dimensions (Ewing & Cervero, 2010). In these studies, the influence of every dimension on travel demand was measured separately using elasticities in the research, and it was found that none of the dimensions, on themselves, had a major effect on travel. But when combined, these dimensions influence travel demand and behaviour significantly (Ewing & Cervero, 2001). The effects of measures of the built environment were investigated on several transport modes, but cycling was underrepresented, as opposed to walking. The mode of walking was mostly related to the number of destinations within walking distance, land use diversity and density of intersections.

Because the built environment is quite broad and complicated, the relevant factors and how these influence cycling in general and in the Netherlands are explained in subchapter 2.3.

2.2.2 Trip characteristics

Distance and travel time are the most important and relevant factors for explaining cycling use. These often have a high level of correlation, and are interchangeable in some cases. In literature, distance has been investigated more extensively. The general consensus logically is that when distance increases, cycling utility decreases. Other modes of transport are then more likely to be chosen. Travel time largely depend on the chosen mode, but the longer the time to be travelled, the smaller the share of cycling (Heinen et al., 2010; Muñoz et al., 2016). These two factors are reflected by the built environment. Aspects as mixed land use, density and infrastructure exert great influence on distances and travel time to destinations (Handy et al., 2014). Another relevant trip characteristic is travel cost. Looking at cycling, the costs of owning a bicycle are relevant, but not nearly as important as the costs of other transport modes. Clear relationships between cycling share and fuel prices have been found, and the costs of public transport have a negative correlation with bicycle use, as cycling is relatively affordable (Heinen et al., 2010). Other trip characteristics worth mentioning are trip purpose and day of the week. The bicycle is more likely to be the chosen mode on weekdays. In general, cycling is thought to be done more for leisure than for other purposes, whereas in the Netherlands all other trip purposes are undertaken by bike as well (Fraser & Lock, 2010; Ton et al., 2019).

2.2.3 Natural environment

Unlike motorized transport, choosing the bicycle as transport mode is strongly dependent of natural factors like climate, weather, elevation and light and darkness. Cyclists are exposed the most to these uncontrollable conditions. The most straightforward factor is elevation or hilliness, which implies the slope of a surface. Generally speaking, more (steep) slopes make cycling less attractive. However, this relation isn't as simple as it seems. Some studies argue that cycling down a hill might make up for the inconvenience of going upwards first, at least for some cyclists. On top of that, recreational cyclists sometimes prefer slopes on their route (Heinen et al., 2010; Muñoz et al., 2016). The influence of weather and climate is less obvious. Starting with climate, it appears that temperate climates are best for cycling shares. Consequently, hot summers and cold winters have a negative impact on cycling utility. A similar effect occurs in daily weather; very hot and cold temperatures decrease cycling shares on those days. In winter, the maximum distance cyclists are willing to do by bike decreases significantly, and short trips are more often done by car or public transport (Ton et al., 2019; Heinen et al., 2010). Concerning daily weather, rain influences cycling the most as regions with a lot of rain usually have a smaller cycling share in their mobility. The factor of darkness has a negative effect on cycling, especially among women (Heinen et al., 2010).

2.3 Associations of the physical environment with cycling behaviour

Besides the literature that focuses on (active) travel in general, there is specific literature available on cycling behaviour as well. While most research on cycling behaviour was first linked to health benefits, the influence of the physical environment on physical activity, and cycling in particular, has become an increasingly studied subject towards the end of last century. The physical and built environment can be subdivided in many categories and factors, and each of these has been associated with cycling behaviour in some way, yet there is no general agreement on these effects (Yang et al., 2019). If there is to be focused on factors that are of relevance to cycling, a framework developed by Pikora et al. (2003) gives a good overview of cycling indicators and the categories these belong to. Additionally, the study found the relative importance of each indicator for cycling as transport mode and as recreational activity. The most important variables for cycling were the continuity of the route, with few places where cyclists have to stop, and the overall traffic safety, which mostly concerned the speed and volume of motorized traffic. As this research also covered walking for transport and recreation, it found that there is a significant difference in the relevance of variables influencing cycling and walking (Pikora et al., 2003).

Whilst most studies are based on results from a specific city or region, there are some comparative studies and some meta-studies reviewing previous work. In an international study involving 14 cities in ten culturally and geographically different countries, four variables were used to determine the influence of the built environment on cycling. These objectively measured variables were: land-use mix (residential, retail and civic), residential density, number of parks and street connectivity. The study found that residential density didn’t affect cycling as transport mode significantly, but that land-use mix and street connectivity are very significant for cycling. Then there were some geographical differences for the importance of parks and green spaces, which is dependent on the local policies and cultures of park use, in order for it to have a positive effect (Christiansen et al., 2016).

In another study, 39 empirical studies on the built environment and cycling behaviour published between 2007 and 2017 were reviewed, in order to find out which built environment factors are the most strongly associated with cycling behaviour (Yang et al., 2019). Cycling was divided into transportation, commuting, recreation and cycling in general, which resulted in different associations with built environment factors. The connections between the factors and cycling types are displayed below in Figure 2.2.

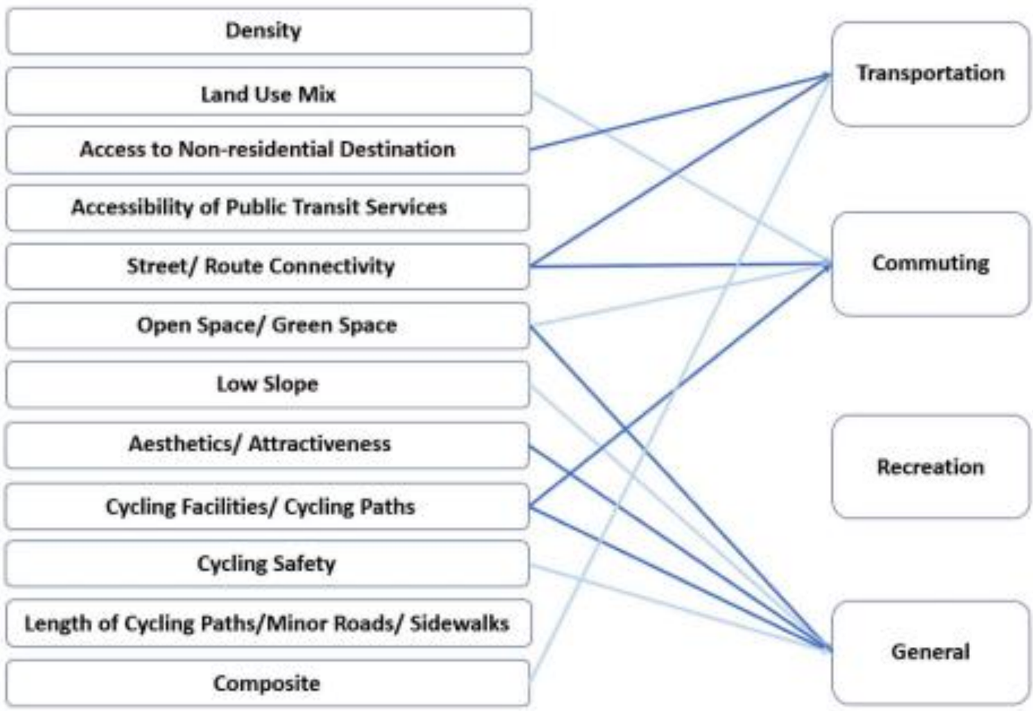

Figure 2.3: Built environment factors and their relation to different types of cycling. Dark blue lines represent a strong association, while light blue lines are used for less strong, emerging associations (Yang et al., 2019).

Access to non-residential destination, street/route connectivity, open/green space, aesthetics/attractiveness and cycling facilities/paths are the most strongly associated with cycling behaviour. Cycling facilities and paths and street and route connectivity even have a strong association with two types of cycling in research, which implies that these factors play an essential role in the measured bikeability (Yang et al., 2019).

In addition to determining the built environment factors that are most strongly associated with cycling behaviour, the factors can be subdivided into motivators and barriers for cycling. Strong motivators can be public transport, aesthetic scenery, good surfaces, etcetera. Barriers that prevent people from cycling can be urban sprawl, poorly maintained roads and public space, litter, and so on (Wang et al., 2016). Four different categories of barriers are distinguished: Opportunity barriers, access and distance barriers, safety barriers and physical setting barriers. For each type of barrier, accompanying measures and characteristics are necessary to overcome these barriers. Respectively for each barrier, examples are reducing the distance, boosting accessibility, improving active transport safety and implement supporting facilities (Wang et al., 2016).

2.3.1 Associations with cycling behaviour in the Netherlands

Most literature that has been discussed so far concerns research that was conducted elsewhere in the world rather than in the Netherlands. Because cycling in the Netherlands plays a more central role in daily mobility than in most countries, it can be expected that the built environment also plays a different role than in other countries. Therefore, this paragraph sheds some light on cycling and the built environment in a Dutch context.

In comparison to the international context, the association of the built environment with cycling behaviour in the Netherlands seems to be slightly different for some factors. One of the most notable differences is the importance of cycling infrastructure for cycling behaviour. While this characterizes the built environment when it comes to cycling, its effect on cycling behaviour isn't as convincing in a Dutch context. Part of the respondents in several studies mentioned that they thought that nothing could be improved infrastructure-wise. This suggests that developing more and/or better cycling lanes and facilities in countries with an already mature cycling infrastructure might not prove to be effective in boosting cycling as transport mode. (Ton et al., 2019; Ton et al., 2017; Engbers & Hendriksen, 2010). However, a study that measured the effectiveness of cycling policy in all Dutch medium-sized cities concluded that improving the quantity and quality of cycling infrastructure does increase bicycle use, but only when combined with measures that demotivate using the car. The first being the *pull factor* for using the bike and the latter being the *push factor* for not using the car (Harms et al., 2016). In a study that explains the success of cycling policy in Denmark, Germany and the Netherlands, these push and pull factors are considered to be essential for the high share of bicycle trips. Among the environmental pull factors, separated cycling lanes, cycling priority at intersections, and sufficient bike parking are the most important; while among the push factors speed limits in neighbourhoods, no priority for cars in many areas and few and expensive parking for cars are some of the most important (Pucher & Buehler, 2008). Unlike in many other countries, Dutch cycling infrastructure already is at a high level, with its high density and continuity of routes, as well in cities as in more rural areas. When it comes to defining the most important determinants of cycling, it seems that personal determinants are at least as effective as environmental determinants. This only holds true for countries where cycling infrastructure is abundant, like in the Netherlands (Engbers & Hendriksen, 2010).

One of the more important similarities between literature in international and Dutch context is the influence of mixed land-use on cycling behaviour. It is evident that mixed land-use is one of the main attractors for cycling and active mode use in general. City centres have a highly mixed land-use and are thus popular cycling destinations and areas (Ton et al., 2019). When it comes to cycling duration, a higher land-use diversity doesn't necessarily exert a significant influence. This may be due to its association with heavy traffic and crowdedness, and these do not benefit cycling behaviour (Gao et al., 2018). However, a high address density, large number of bus stops and proximity to a train station makes people cycle longer distances (Gao et al., 2018).

Regarding city size, it appears that small and medium sized cities are positively associated with cycling. Out of the five largest Dutch cities, only Rotterdam has a negative effect on cycling behaviour, compared to the other cities. This can be explained by the city's history, as it was completely rebuild after it had been destroyed in the second world war. The car was booming in the 70's and 80's and this resulted in a car-oriented city, which makes it less suitable for cycling. In countries where cycling is integrated in daily mobility it acts as competitor for the car, while in countries where cycling is unusual public transport acts as competitor for the car (Ton et al., 2019).

Whereas there certainly are similarities between the international and Dutch context regarding the influence of environmental determinants for cycling, comparing them should be done with caution. Especially infrastructure has different explanatory power for cycling in cycling-oriented countries, and there are other factors that influence cycling behaviour to a different extent. These differences can all be attributed to the maturity of the bicycle as transport mode in the Netherlands. This maturity is reflected not only in terms of infrastructure, but also in the comprehensive policy, spatial structure, car-restricting measures, culture and education (Pucher & Buehler, 2008).

2.4 Individual aspects

Alongside the physical environmental aspects that are fundamental in this research, there are some individual aspects to cycling that need to be taken in regard. Several basic characteristics of the population prove to be important for explaining active mode choice and cycling in particular. Besides these, psychological factors play a part in this choice as well, in particular perceptions of the environment.

2.4.1 Socio-economic and demographic characteristics

In literature, several significant relationships between population characteristics and cycling behaviour have been found. The most common population characteristics that have a strong connection to cycling for transport are age, gender and income; these are included in most studies that explain (active) mode choice (Heinen et al., 2010; Muñoz et al., 2016; Handy et al., 2014). Starting off with gender, most research shows that men cycle more in most cases, even though they tend to live further away from work (Muñoz et al., 2016; Heinen et al., 2010). However, this only holds for countries where cycling is not as common as in the Netherlands for example. In countries with high cycling rates, women use the bicycle just as much or even more in some cases (Goel et al., 2021). As for age, the relationship with cycling isn't very clear in research. It is evident that cycling is influenced by age, but there is no general consensus on how exactly. Most research claims that cycling is negatively correlated with age. Especially in the Netherlands, children and adolescents are the largest group of cyclists (Heinen et al., 2010; Ton et al., 2019).

Furthermore, income level affects cycling behaviour, although research has produced contradictory results. Negative as well as positive and unsignificant correlations between income and cycling share have been found. A potential explanation for this is the ambiguous effect of having a high income: it makes it possible to invest more in a good bicycle, which would increase bicycle use. Besides this, people with higher income tend to maintain a healthy lifestyle more than those with low income. On the other hand, a high income implies having a greater budget for transport, and thus makes driving a car more affordable. Owning a car automatically decreases bicycle use (Heinen et al., 2010). In the Netherlands however, increased car ownership over the last few decades hasn't had this effect on cycling. Looking at other transport modes, it is evident that public transport is positively correlated with cycling. This is because cycling fulfils the role of complementary transport to and from stations. Additionally, people with a high level of education make use of the bicycle more than lower educated people. This is consistent with the positive relation of students with the use of the bicycle. Finally, ethnicity generally doesn't explain cycling behaviour, but in the Netherlands native Dutch people use the bicycle more (Ton et al., 2019).

2.4.2 Perceptions of physical environment

The aim of this research is to determine the bikeability which is mostly based on characteristics of the physical environment. Socio-economic and demographic characteristics are also of influence on transport mode choice, and thus on the cycling share in a neighbourhood. Furthermore, it is important to distinguish and explore some social and psychological characteristics of inhabitants, which includes their perceptions of the physical environment in particular. For example, cyclists and non-cyclists may perceive the physical environment in a different way, which has consequences for the perceived bikeability. Accordingly, knowledge about this comes in handy when data from the survey among inhabitants is analysed and needs explaining. Willis et al. (2015) have found, by conducting a meta-study, the most important social and psychological aspects that explain cycling behaviour and their connection to the built environment. The influence of perceptions is undeniable, especially that of barriers and benefits to cycling, and of traffic safety. Besides these, the perception of cycling routes is relevant for the built environment too.

Next to perceptions, there are attitudes, habits and the influence of friends, family and colleagues that are explanatory for cycling behaviour. Especially in a cycling-oriented country like the Netherlands, the social and psychological factors can outweigh the physical environment factors. This proves that the built environment is not the only factor to be taken into account by city planners, although it remains essential as improvements of the built environment can in turn affect perceptions (Willis et al., 2015). In another study involving research in 17 cities across multiple continents, perceptions were mostly linked to the physical elements of the neighbourhood. Cycling as transport mode was significantly determined by perceived infrastructure, design, street connectivity, mixed land-use, safety, and perceived distance to destinations (Kerr et al., 2016). When perceptions of cyclists are compared to the views of city planners on cycling in the city, some similarities and differences stand out. Both sides agree that separated cycling lanes along main roads are crucial for cycling as transport. But, cyclists put more emphasis on the beneficial effects of green space and the natural environment along cycling routes. They are even willing to take detours if that results in a more pleasant route, incorporating the natural environment, avoiding heavy traffic, and escaping noise and air pollution. These factors were seldom considered as important by city planners (Marquart et al., 2020).

2.5 Bikeability index

In the first part of the theoretical framework many of the determinants of cycling behaviour have been discussed and elaborated, with a special focus on the physical and built environment. In order to determine how the bikeability can be measured best, the most important, relevant, and also most suitable aspects for analysis have to be selected. As measuring the bikeability involves a spatial analysis based on geographic data, the individual aspects are left out of the analysis. After all, there's no geodata for the city of Nijmegen about perceptions, socio-economic and demographic characteristics that can be directly linked to a spatial property like bikeability. However, these will prove to be useful in the survey, the second part of the research. Considering the natural environment aspects, the elevation is a useful and very suitable indicator for bikeability (Yang et al., 2019). The Netherlands has its own detailed elevation program that is publicly accessible (Publieke Dienstverlening Op de Kaart (PDOK), n.d.). The other aspects of the natural environment are either subject to constant change or aren't interesting on a local scale, like the climate. The trip characteristics are included in the physical environment according to literature, but are greatly influenced by the built environment. Trip characteristics also vary considerably from time to time due to individual characteristics, traffic, weather and so on. However, the shortest distance to and from destinations is relatively constant, as roads and shortest routes don't change so often.

The built environment evidently plays the largest role in measuring bikeability, but it also includes more relevant factors than actually can be used. According to the discussed literature, there is no doubt that land use is one of the most influential for cycling behaviour and bikeability. Mixed land use is also of importance and is beneficial for cycling (Christiansen et al., 2016; Yang et al., 2019; Ton et al., 2019). Next, cycling infrastructure is essential for the share of cycling, especially when taking safety in consideration (Yang et al., 2019; Pikora et al., 2003). Especially the quality is relevant, as the quantity of bikeable roads is not a problem in the Netherlands (Harms et al., 2016; Pucher & Buehler, 2008; Engbers & Hendriksen, 2010). Finally, the fourth aspect considered as one of the most important, is connectivity of streets and routes (Christiansen et al., 2016; Yang et al., 2019; Pikora et al., 2003; Pucher & Buehler, 2008). Other seemingly important factors, like aesthetics, green space and density, were not as convincing in explaining cycling behaviour across all literature, or are difficult to grasp in a geodata-based analysis.

The appropriate aspects for analysis have been determined. This leads to the choice for a certain tool that is suitable for measuring bikeability. The leading theory about the physical determinants of cycling central in this thesis, is the bikeability index. The bikeability index is developed by Winters, Brauer, Setton and Teschke (2013) and focusses mainly on the components of the built environment. The index is designed and meant as a spatial tool to support sustainable travel, by identifying how well suited an area is for cycling as transport. In order to develop the index, results of focus groups, travel behaviour studies and opinion surveys were used and compared. Factors that were important according to all three methods have been included in the index. The index was then mapped across the Vancouver metropolitan area, using geographic information systems (GIS). The influence of the factors on cycling was then determined by doing research in several focus groups, consisting of different groups of people with different cycling behaviour. The resulting ranking of the factors is displayed in Table 2.1.

Rank	Factor	Example quote from participant	Score[a]
1	Bicycle facilities	"The more you feel separated from traffic, the safer you feel."	50
2	Traffic	"The encroaching volume of traffic is rendering the bike lanes inadequate."	25
3	Street network	"If I'm commuting I find [grid network] much easier, I feel I can progress through much faster."	17
4	Topography	"Hills are a big problem for me because I don't have the strength or endurance."	16
5	Environment	"I just hate it—all types of pollution—I would go a long way out of my way to avoid it."	12
6	Distance	"If I could ride to work from home in a half hour, I wouldn't think twice about it."	9
7	Neighbourhood land use	"I don't find the suburbs set up for bicycles. It's not easy to do your everyday chores because of the distances."	4
8	Population density	[no comments]	2

[a] Factors were prioritized in order of importance to participant. Priority 1 was assigned 3 points, priority 2, 2 points, and priority 3, 1 point. Total points = 135. 23 individuals completed the ranking exercise, and one person assigned only 2 factors.

Table 2.1: Prioritized factors of bikeability in order of importance in focus groups of (potential) cyclists. Derived from "Mapping bikeability: a spatial tool to support sustainable travel". Winters, M., Brauer, M., Setton, E. M., & Teschke, K. (2013).

A number of four domains were found that appeared to consistently influence cycling: Bicycle facilities, connectivity (street network), topography, and (neighbourhood) land use (Winters et al., 2013). The other domains and components in the table are of importance to cycling as well, but these cannot be directly linked to the built environment. The domain of bicycle facilities has been divided into the availability and quality of the bicycle facilities. Matching variables and indicators for the components were used, combined and overlayed on each other, resulting in a comprehensible map, which gives a good overview of the more bikeable and the less bikeable areas in the Vancouver metro area. The bikeability index isn't only a tool to map the bikeability of an area, it provides insight in the spatial cycling structure as well. By gaining insight into the bikeability of an area, a well-targeted approach towards cycling in urban planning can be developed, which can result in a more suitable cycling policy. (Winters et al., 2013).

The five components are operationalised by choosing quantifiable factors that can also be mapped using existing geodata. In Table 2.2 below, each component has been assigned a certain range of values, matching with the eventual bikeability score ranging from 1 to 10. As these values are based on research in Vancouver, they would require some adaptations before being used for research in Dutch cities.

Score[a]	Bicycle route density (m of bicycle routes)[b,c]	Bicycle route separation	Connectivity of bicycle-friendly streets (number of intersections)[b,c]	Topography	Destination density (number of bicycle-friendly destinations)[b,c]
1	0	no	0	> 20	0
2	> 0–250		1	10–20	0
3	> 250–450		2–3	7–10	1–2
4	> 450–600		4–6	5–7	3
5	> 600–750		7–10	3–5	4–5
6	> 750–850		11–15	2–3	6–8
7	> 850–1100		16–20	1–2	9–10
8	> 1100–1400		21–25	0.5–1	11–20
9	> 1400–1800		26–30	0–0.5	21–40
10	> 1800–6000	yes	31–60	0	40–300

[a] 1 = low bikeability, 10 = high bikeability.
[b] deciles based on empirical data from the Metro Vancouver area.
[c] in 400 m (1/4 mile) radial buffer.

Table 2.2: Values of bikeability components converted to a 1 to 10 score. Derived from "Mapping bikeability: a spatial tool to support sustainable travel". Winters, M., Brauer, M., Setton, E. M., & Teschke, K. (2013).

2.5.1 Limitations and adaptation to Dutch context

The bikeability index is a clearly organized tool that measures which areas are more and less convenient for using the bicycle. Therefore, it serves as a good benchmark and starting point for the framework that is developed in this chapter. However, the index has some drawbacks that need to be addressed. The index was developed based on research in the Canadian city of Vancouver. The structure of North American cities, like Vancouver, is very different than that of Dutch medium-large cities. Dutch medium-large cities have a more dense and close-knit spatial structure, compared to large Canadian cities that have a lot of urban sprawl. Dutch cities, and European cities in general, have grown in a predominantly organic way, while North American cities have a more planned, grid-like structure, characterized by the numbered streets and blocks (Besussi & Batty, 2010). On top of that, North-American cities rely mostly on car mobility. The infrastructure and spatial structure of the city is aimed at car traffic rather than cycling and walking. Because of this, cycling isn't as popular as in the Netherlands, which may be of influence on the usefulness of the bikeability index for Dutch cities (Philipsen, 2018).

Therefore the operationalisation of the components in the bikeability index needs some adaptations in order to be suitable for the city of Nijmegen. First off, bicycle route quality and quantity, in the index measured as density of bicycle routes and cycle lane separation, are merged as one component. Because the density of bicycle routes in Dutch cities is almost equal to the total road network, analysing this component is not of added value to the Dutch adaptation of the index.

The merged indicator indicates the type of cycling facility and it automatically includes all bikeable routes. Connectivity of streets is represented by the number of intersections in an area in the index. This might work well in a grid-like street network in a city like Vancouver, because the more intersections there are, the more equally fast routes are available. In the Netherlands however, more intersections mean more places to cross the streets and more traffic lights that hold cyclists up. Because Dutch cities have an organic form, having more intersections doesn't necessarily result in more equally fast routes. In order to analyse connectivity in a reliable way, space syntax is used to calculate the level of integration of the municipal road- and path network. Concerning the factor of topography, sticking with the slope calculation in the index makes sense, as steep slopes have an adverse effect on cycling everywhere. Finally, the destinations density used in the index is suitable for the Dutch context, but in the analysis the destinations are subdivided in seven categories, excluding residential destinations. Further operationalisation and methodology of the bikeability analysis in GIS is explained in the next chapter.

2.6 Conceptual model

This theoretical framework is concluded by the conceptual model in Figure 2.4, which connects the different theories and literature in a comprehensible and clear way. Emphasis is put on the relationships between the bikeability components and the two different types of bikeability, that lead towards an improved bikeability index in the end. The model provides guidance throughout the rest of this thesis.

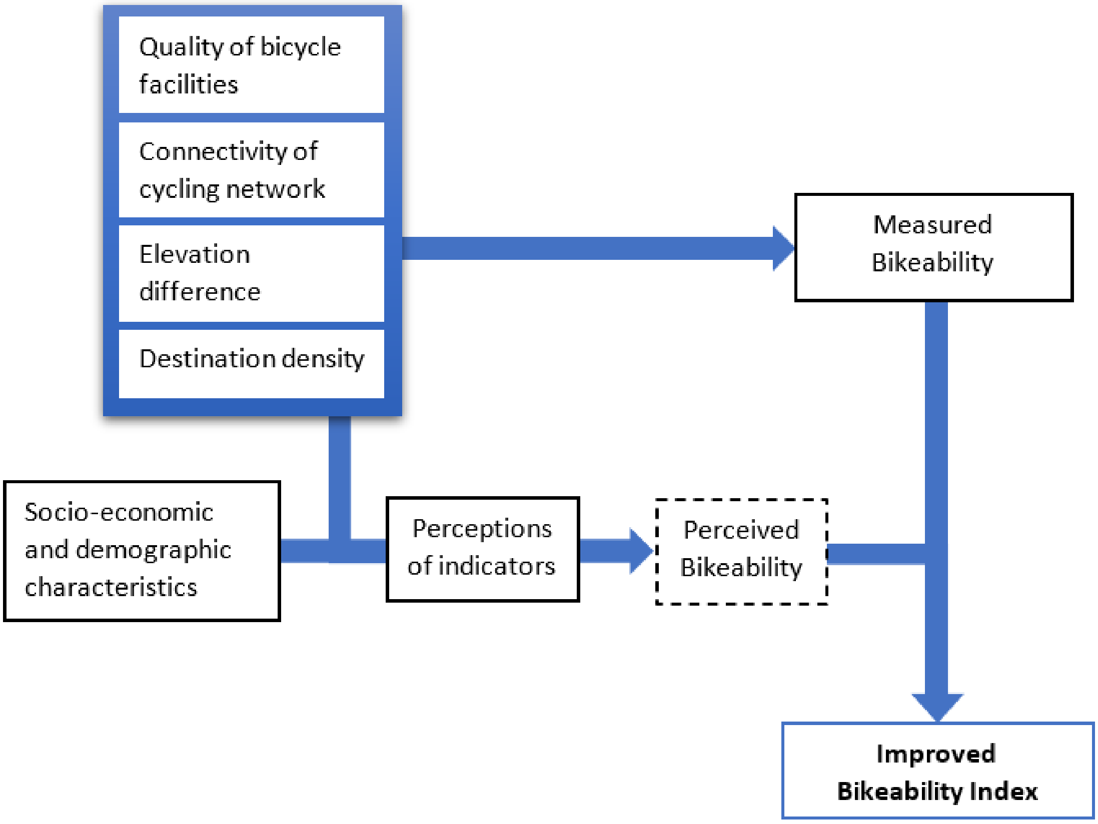

Figure 2.4: Conceptual model/framework

3. Methodology

Doing research asks for a clear and sound research design, which also includes the methodology. In order to accomplish what this research aims for and to answer the main research question, the research strategy and methods that are being used are explained in the following chapter. The first part of the chapter involves the paradigms this research can be categorized in. This is followed by an explanation of the research strategy. Then the chapter moves on to the research methods and collection of data, also focusing on the research material and the analysis of the data. Finally, the principles of reliability and validity and their position in this research are discussed.

3.1 Research paradigm

The methods and approach that have to be chosen in the research are, for a large part, dependent on the paradigm the research is embedded in. A paradigm or worldview can be defined as "a basic set of beliefs that guide action" (Guba, 1990, p.17). This set of beliefs influences the preferences of a researcher carrying out a study. The most relevant paradigms have evolved over time, and often a research combines approaches from different paradigms (Creswell, 2016). Generally, four major paradigms in research can be distinguished, with some having several names in literature. The first is the positivist paradigm, which is characterized by absolute, indisputable facts and theories. Knowledge can only be obtained through a sound scientific method and the following results and theories form a reality that remains the same. There is doubt whether this approach is useful in social sciences, because it doesn't allow other interpretations of reality. This is also the difference with post-positivism, which does believe in multiple perspectives. Positivist research is always quantitative of nature. The second paradigm is social constructivism (also called interpretive paradigm), which is a completely different worldview. Reality is open to interpretation and knowledge is obtained by seeking a deeper understanding of research subjects. This happens through qualitative research in which the ideas and views of participants are essential, as opposed to the researchers' power in positivism. The third paradigm is the advocacy/participatory paradigm, also known as critical paradigm/theory. Having more similarities with constructivism than with positivism, this worldview is focused on social and political issues. It questions and tries to transform discourses constructed through history and addresses issues like inequality, oppression and discrimination. Research embedded in this paradigm contributes to improving the lives of the underprivileged (Creswell, 2016; Guba & Lincoln, 1994; Rahi, 2017). The fourth and last paradigm is pragmatism, which is not bound to any philosophy or system of methods. This worldview specifically focuses on the problem and on understanding it. Any research method, technique and strategy can be used, as long as it is suitable for the problem in question (Creswell, 2016; Rahi, 2017).

In this study, the research question is as follows: *What does a 'bikeable' neighbourhood entail for residents of low socio-economic status and how does this compare to the objectively measured bikeability?* This question can be divided into two parts; the first one being an objective measure of a phenomenon, carried out using only quantitative data and not taking into account other perspectives. This part of the research is of post-positivist nature. The second part, however, is focused on individuals' perception of the phenomenon, which allows different opinions and perspectives, and might contradict or confirm the results of the quantitative research. So this part of the research is of social-constructivist nature. Focusing the research on what the phenomenon is to the inhabitants of the neighbourhoods the research is about, characterizes parts of the participatory paradigm. It can be said that the research shares common ground with the first three paradigms. Therefore, the research is all the more pragmatic, as it combines different strategies and methods (quantitative and qualitative) to answer the main question. Combining methods and strategies implies going for a mixed methods approach, which is a characteristic approach within the pragmatism paradigm (Rahi, 2017). The overarching strategy that is used to accomplish the research goal and answer the main question, is a case study. Within the context of the case study, a quantitative GIS-analysis as well as a partly qualitative survey are applied. The choice for this strategy is explained in the next paragraph, as well as the details of the strategy in question.

3.2 Research strategy and methods

In order to conduct the research, several choices regarding the strategy have to be made. As discussed in the first paragraph, this thesis consists of multiple strategies fitting into a mixed methods approach. To start with, it can be convenient to distinguish the general methodological choices made. Verschuren and Doorewaard (2015) propose three types of choices the researcher has to make. These are between broad or in-depth research, empirical and theoretical research and qualitative and quantitative research. Respectively, this research consists of in-depth, empirical research, using both qualitative and quantitative data. Besides this, the thesis operates on a deductive level, where a theoretical framework functions as point of departure before data is collected (Rahi, 2017).

When it comes to choosing the main research strategy, the case study is the most suitable for answering the research question. A case study is characterized by the possibility of doing thorough, in-depth research, which can provide the researcher with a more complete understanding of the phenomenon of bikeability. Normally, conducting a case study means that the methods used are qualitative, yet within this case study quantitative methods are mostly used (Williams, 2007). There are different approaches for combining mixed methods with a case study, but in this study a choice for the Case Study – Mixed Methods design (CS-MM) has been made, displayed in Figure 3.1 (Guetterman & Fetters, 2018). The case study consists of two homogeneous neighbourhoods in Nijmegen that share some important features, namely Wolfskuil and Willemskwartier. The two neighbourhoods are purposively chosen based on theoretical grounds and can be called non-probability samples (Van Thiel, 2017). The multi-sited case is chosen based on the location of the neighbourhoods within the city and their demographic and spatial properties. A detailed case description is provided in chapter four.

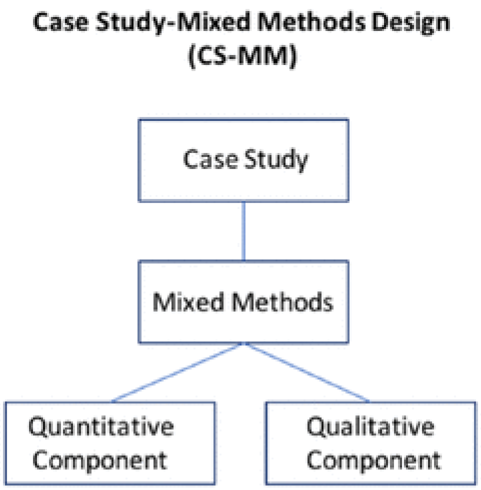

Figure 3.1: CS-MM: A nested case study is investigated using both a quantitative and qualitative component (Guetterman & Fetters, 2018)

Following the choice for the case study, a purely quantitative method is applied to measure the objective bikeability. The method chosen for this part of the research is desk research. To be more precise, a GIS-analysis is carried out over the areas of Wolfskuil and Willemskwartier. The data used for this method is secondary, coming from openly accessible databases of existing spatial data. Desk research is not empirical on itself, because the data isn't coming from a primary data source. However, by collecting specific spatial datasets per indicator of bikeability and merging these datasets into one thematic map, a new visual representation of the objective bikeability is created. The collection of data is based on the indicators presented in the *bikeability index* in the theoretical framework, and will be further explained in the following paragraph.

The second part of the case study also concerns a predominantly quantitative method, however with a qualitative aspect. After the GIS-analysis is done, the objective bikeability in each neighbourhood, according to the index, is visualized. As discussed in chapter two, this index is developed in a different urban context and might not be fully representative for this thesis' case study. Therefore, applying a second research method can provide extra and new information of the bikeability in this case study (Yin, 2011). A questionnaire is designed with the purpose of investigating the bikeability as it is perceived by the inhabitants of Wolfskuil and Willemskwartier. The questionnaire is part of a survey and is mostly used to collect quantitative data, however qualitative data can be gathered as well. It is a tool meant for collecting large amounts of data.

3.3 GIS analysis

The first part of conducting the research concerns an analysis of existing data, by using a Geographical Information System (GIS). The software that is used for this part of the research is QGIS, a free and open-source computer program. QGIS was chosen over ArcGIS because it is free to download and more easy to run on a laptop, while it doesn't compromise on possibilities.

The analysis includes the four different characteristics that have been discussed in the theoretical framework. To make these characteristics suitable for a GIS-analysis, corresponding data sets that are publicly accessible are essential. The procedure for making the data ready for analysis is explained below per indicator. Every indicator is visualized by a final (raster) layer and then these final layers are combined to create a cartographic image of the bikeability in the municipality of Nijmegen. All pixels on the raster layers are scaled to have a value of 1 to 10, in order to respectively indicate low and high bikeability. Initially, every indicator carries the same weight in this semi-final product. The final step of this analysis comes after the survey is analysed. The indicators are then ranked and weighted using the perceived importance according to the respondents. An elaborate description of the procedure to be followed is included in the appendix.

Quality of bicycle infrastructure

The quality of cycling lanes, and roads in general, is determined by the type of cycling lane. Separation from other traffic plays a large role in this and improves the quality of the lane. In order to analyse this for every street in Nijmegen, part of the National Road Database *(Nationaal Wegen Bestand, NWB)* is downloaded from PDOK, which is the main platform for governmental geo-data. The NWB contains several different data files, but for this analysis the heart lines are most suitable, as these indicate the centre of roads, paths and cycling lanes (PDOK, n.d.). The road database consists of segments and for this analysis every segment is assigned with a value that says something about the separation. Several characteristics of these road segments are embedded in the data as attributes, but the separation of cycling lanes is not yet included. As this information is not available as such, all roads, lanes and paths in the municipality have to be observed and assigned a value manually, using Google Street view and Open Street Map (OSM). Four levels of separation are distinguished: no separation, a marked cycling lane (yet not physical barrier), a physically separated lane and a so called 'cycling street', a street fully prioritised for cyclists. This results in a shapefile consisting of lines with different colours, indicating different levels of separation.

Street connectivity

Street connectivity is a less straightforward indicator, as it's hard to quantify or visualize connectivity. One scientific method to measure the interconnectivity of spaces and lines is space syntax. '*Space syntax* is a science-based, human-focused approach that investigates relationships between spatial layout and a range of social, economic and environmental phenomena.' (space syntax network, n.d.). One of the applications of this spatial analysis tool is the integration (connectivity) of roads (called axes and segments) within a road network. In this case, it can calculate the integration of roads within the municipality of Nijmegen. The same *National Road Database* is used for this, but separated bicycle lanes are left out in this case, because it would count these as extra roads, which would distort the level of integration. The network of lines is analysed in *depthmapX*, an open source spatial analysis software optimised for space syntax, performing a segment analysis (University College London, n.d.). The results are transferred to QGIS and the map is adjusted to optimally visualize the connectivity.

Land use (destination density)

Land use is a pretty broad indicator, so in order to analyse it, the density of destinations that are reachable by bike is used. The basis of this analysis is a layer that contains points of the general registration of addresses and buildings (Basisregistratie Adressen & Gebouwen, BAG) (PDOK, n.d.). Within the layer, there's a feature that indicates the function of the building. A separate layer is made for every function, as the functions equal different destinations. The residence function is left out, as these are private properties rather than accessible destinations. Each point layer is transformed into a heat map and these heat maps are then combined to form a comprehensive heat map showing where the accessibility to destinations by bike is best.

Topography (elevation and slope)

The main aspect of topography is elevation in this case. Analysing this indicator implies measuring the slope in Nijmegen. Doing this requires a map that shows the elevation on a very detailed level. On the website of PDOK, small scale maps showing the elevation of every area in the Netherlands are available. These form the general elevation database of the Netherlands (Actueel Hoogtebestand Nederland, AHN) (PDOK, n.d.). All required maps of the municipality of Nijmegen are merged into one layer, which is followed by a calculation of the elevation difference between each raster point, better known as the slope. The colours of the resulting layer are changed in order to visualize where the steepest slopes and thus roads are located.

Score	Quality of bicycle infrastructure (different types of cycling lanes)	Connectivity of road network (level of integration)	Land use mix (Combination of different destination densities)	Topography (slope in percentage)
1	Areas without roads	1300 – 1529	1 – 1,99	>18
2	No cycling facility	1530 – 1759	2 – 2,99	10 – 18
3		1760 – 1999	3 – 3,99	7 – 10
4		2000 – 2229	4 – 4,99	5 – 7
5	Marked lane	2230 – 2459	5 – 5,99	4 – 5
6		2460 – 2689	6 – 6,99	3 – 4
7	Physically separated lane	2690 – 2919	7 – 7,99	2 – 3
8		2920 – 3159	8 – 8,99	1 – 2
9		3160 – 3389	9 – 9,99	0 – 1
10	Cyclists' street	3390 – 3620	10	0

Table 3.1: Bikeability scores and accompanying values per component. Based on Table 2.2 (Winters et al., 2013).

In Table 3.1, the bikeability scores and respective scores per indicator are displayed. Some remarks for the chosen values:

- For the level of separation, 'no separation' is equal to a bikeability score of 2. This is due to the fact that the road network doesn't cover the whole surface of the municipality of Nijmegen. Places with no roads also need a value from 1 to 10 in order to calculate the bikeability for the whole surface of Nijmegen, therefore a score of 1 is assigned.
- The values for the level of integration are calculated outcomes of the segment analysis.
- Land use mix is measured by combining seven different destination densities. The density value for each destination varies a lot, hence the values in the table are equal to the bikeability score.
- The values for the steepness of slopes are expressed in percentages. This means that for a slope of 10% the road climbs one hundred metres for every kilometre in length.

3.4 Survey

3.4.1 Questionnaire

The case study questionnaire is divided into two parts. The first part consists of closed questions, that ask respondents about their perceptions of the bikeability factors in the whole city and in their own neighbourhood. Per indicator three or four questions are posed, resulting in 13 closed questions. The main purpose of these questions is to find out if the respondents rate the bikeability indicators differently in the whole city than in their own neighbourhood. Every question uses a 5-point Likert scale as response option. The possible answers normally range from 'strongly agree' to 'strongly disagree', or something similar. The middle answer is neutral by nature, 'neither agree nor disagree' for example. Because perceived bikeability depends on opinions and attitudes, using Likert scale questions makes it possible to measure and quantify these on a metric scale. Besides this, Likert scales are easy to read and understand if used consistently, thus producing reliable data. On the other hand, a weakness of this method is that answers can be biased, as respondents may avoid the extreme response categories to please the researcher or out of social desirability (Bertram, 2007).

The second part of the questionnaire includes three questions, starting off with a ranking of the four previously addressed aspects. Then an open question is posed that asks respondents to think about possible other aspects of the physical environment that they find important or relevant. The last question implies ranking this/these extra aspects among the existing aspects, in order to find out how important this is to the respondents. The full questionnaire is included in the appendix.

In most cases, a questionnaire is limited to closed questions with fixed options for answers, which makes it easier to standardize data analysis. Implementing open-ended questions reduces the options for statistical analysis of collected data and makes analysing more time consuming (Van Thiel, 2017). However, the reason for choosing this type of survey is that the respondents have to think about factors that they value as important during cycling. With this type of qualitative information from the questionnaire, a smaller amount of respondents can provide fresh, new insights. Accordingly, it is possible to gain a more complete and substantiated understanding of the bikeability as it is perceived by the respondents (Guetterman & Fetters, 2018).

The research population of this survey consists of inhabitants of the two neighbourhoods in the case study; Nije Veld and Wolfskuil. Not included in this population are inhabitants younger than 14 and older than 74, which results in a total research population of 9682 inhabitants (Gemeente Nijmegen, 2021). The total number of respondents that have completed the questionnaire is 53. This may seem like a relatively small sample of respondents for a population this size, but the questionnaire is not the dominant method in this research. The survey results are meant to provide insight in the perceived side of bikeability, in order to adapt the original index of Winters, Brauer, Setton and Teschke (2013) to the context of Nijmegen, and eventually improve it. Since there is a qualitative component in the questionnaire, personal and detailed answers of respondents allow for a smaller sample.

3.4.2 SPSS Analysis

In order to analyse the gathered data from the questionnaire, the statistical analysis program SPSS is used. Different types of analyses and tests are used to discover possible significant relations between different variables, and to find significant differences between two or more variables.

Linear regression

This type of regression is very common and is used to find significant linear relations between two variables. For example, higher values of independent variable A may lead to significant lower values of dependent variable B. In this research, singular linear regressions are used to find possible linear connections between each of the respondents' characteristics (gender, neighbourhood, age and income) and each of the perceived bikeability aspects and importance of aspects.

Wilcoxon signed-ranks test and Friedman test

The test that is used the most in the SPSS analysis is the Wilcoxon signed-ranks test. This test is the non-parametric alternative to the paired-samples t-test, that assumes normality of variables. In this study however, all of the dependent variables have a non-normal distribution due to the question types in the questionnaire. All answers are recorded on Likert scales (1 to 5) and as rankings (1 to 4), which are both ordinal, or on a nominal, dichotomous scale (yes or no). Together with the relatively small sample size, non-parametric tests are the best option for accurate analysis of the survey data (Field, 2013). This test compares the signed ranks of two dependent variables to determine if these score equally or not. Therefore, it is used to compare the answers to the perceived bikeability questions for Nijmegen and for the neighbourhoods. Moreover, it is used in combination with a Friedman test to determine if indicators are ranked differently. The Friedman test does the same, but requires three or more variables. The Wilcoxon test is used to identify which rankings differ after a significant difference between any of the rankings is found. For this type of test a Bonferroni correction is used.

Mann-Whitney test

This non-parametric test is used to determine if the two groups of a nominal independent variable have equal values for a set of dependent values. It is an alternative to the more common independent samples t-test, but the latter requires the dependent variable data to be normally distributed. While the Wilcoxon signed-ranks test is applied on related variables, this test works the same for independent variables (Field, 2013). The Mann-Whitney test is used to discover if gender and neighbourhood are significant predictors for the ranking variables and for the perceived bikeability variables.

Kruskal-Wallis test

The next statistical test to be used is the Kruskal-Wallis test. This test is very similar to the Mann-Whitney test, but it is suitable for independent variables consisting of three or more groups. Therefore, it's an alternative to a normal ANOVA that doesn't assume normal distribution of variables (Field, 2013). In this study it is used to determine if different age and income groups have equal scores for ranking variables and perceived bikeability variables. If there's found some significant difference between any of the groups, a Post Hoc test is carried out to find between which groups differences in scores are occurring. The Post Hoc test in question is again the Bonferroni correction.

T-test and one-way ANOVA

As opposed to the preceding non-parametric tests, the 'regular' independent samples t-test, one-way ANOVA and paired samples t-test are still used when it comes to analysing the accumulated perceived bikeability scores. This variable is added to the data set as a result from adding up the values for every perception variable per respondent. Not only the total accumulated score is calculated, the scores for just the citywide variables and the neighbourhood variables are added as separate variables. This calculation makes these new variables normally distributed. To determine if the independent variables can predict the accumulated bikeability scores, an independent samples t-test (for gender and neighbourhood) and a one-way ANOVA are conducted. To find significant difference between the accumulated neighbourhood and citywide scores, a paired samples t-test is carried out (Field, 2013).

3.5 Reliability and validity

Reliability and validity are two core principles that need to be taken into account when conducting research. Reliability is determined by the accuracy and consistency of the research. Accurately collecting data improves the reliability. Consistency concerns the repeatability of the research. Will the results be the same when the study is done again in the same way? Validity can be divided in external validity and internal validity. The internal validity considers if the study investigates what it is supposed to investigate. This implies choosing the methods that are most suitable for answering the research question. The external validity determines whether it is possible to generalize the outcomes of the research; are the conclusions applicable to other, comparable situations or cases? The quality of the conclusions of a research are dependent on these two conditions (Van Thiel, 2017). Normally, the strength of the case study are the internal validity and reliability that come with it, due to the large amount and variety of data that is collected to make statements about the case. However, the external validity of the case study design is therefore limited, as the knowledge is very detailed and case-specific.

In order to improve the validity and reliability of this thesis, the principle of triangulation plays a pivotal role in the research strategy. Triangulation means that more than one method is applied in the research. By having two or more methods, one method is able to check on the reliability of the other method, and the other way around (Guetterman & Fetters, 2018). As discussed in the previous paragraph, the GIS-analysis of the neighbourhoods is followed up by a questionnaire that is aimed at finding differences and similarities with the objective bikeability. Using this mixed method approach within the case study improves reliability and external validity. Investigating how well suited the bikeability index is for comparable neighbourhoods in the Netherlands is actually focused on the generalizability of this index, and thus the external validity.

4. Case Study

This research focuses on the city of Nijmegen, the largest city and municipality in the province of Gelderland. The research is carried out by using the characteristics of the physical environment. These characteristics are part of what makes Nijmegen a unique city, as every large city is unique on itself. Therefore, the specific results regarding the bikeability of this case study are not easy to generalise for other cities. Yet the components used and their ranking of importance can be relevant and useful for measuring bikeability in other cities.

Apart from the city in its entirety, the case study is narrowed down to two neighbourhoods. In order to carry out a survey amongst the population, focusing on a smaller area is a more viable and reliable method for gathering data. The neighbourhoods that have been chosen are Wolfskuil and Nije Veld.

4.1 Nijmegen

4.1.1 Geography

The city is situated alongside the river Waal, which actually is the Dutch part of the Rijn. The Nederrijn, which flows through the city of Arnhem, is a somewhat smaller branch of the Rijn. The origins of Nijmegen were first built on the banks of the Waal as part of the Roman empire. The city has since then expanded mostly to the west and south, with the river in the north being a natural barrier. After the second world war, the surrounding villages of Hatert, Hees, Neerbosch and Brakkenstein were swallowed by the growing city and became neighbourhoods carrying the same name. In the 1960's and 70's large new city expansions were built in the west and southwest, known under the names of Lindenholt and Dukenburg. All these expansions in the same direction made the city very unbalanced, as the city centre was in the northeast and new neighbourhoods were built up to seven kilometres southwest. In the 1990's, the city began to expand north of the Waal for the first time. A large Vinex construction project in the 21st century, called Waalsprong, meant the incorporation of the villages of Lent, Ressen and Oosterhout in the municipality of Nijmegen. There are three bridges that connect the south of the city to the north, being the Waalbrug east of the centre, the Spoorbrug west of the centre and the new Oversteek, which was built in 2013, on the far west side of the city.

Another geographical characteristic of Nijmegen is the elevation difference, shown in Figure 4.1. This relief was created by levees during the last ice age. The east and southeast are significantly more elevated than the other parts of the city, which could make the city less attractive for cyclists, due to (steep) slopes in some parts. Regarding the accessibility and mobility of the city, Nijmegen has a total of five train stations, with the central station being the most important. The other stations are Goffert and Dukenburg (to the southwest), Heyendaal (to the south) and Lent (to the north). Further public transport within in the city is operated by buses running on biogas. By car, there are several large access roads, amongst which the A325 in the north and the A73 in the west are the most important. In the east, the German border is not far away. Besides this, cycling is one of the most important transport modes and Nijmegen therefore has an extensive cycling network. There are numerous fast cycling routes within the city's boundaries connecting all neighbourhoods and districts. On a regional level there are fast cycling routes as well, such as the RijnWaalpad, which connects the centres of Nijmegen and Arnhem (Gemeente Nijmegen, 2019).

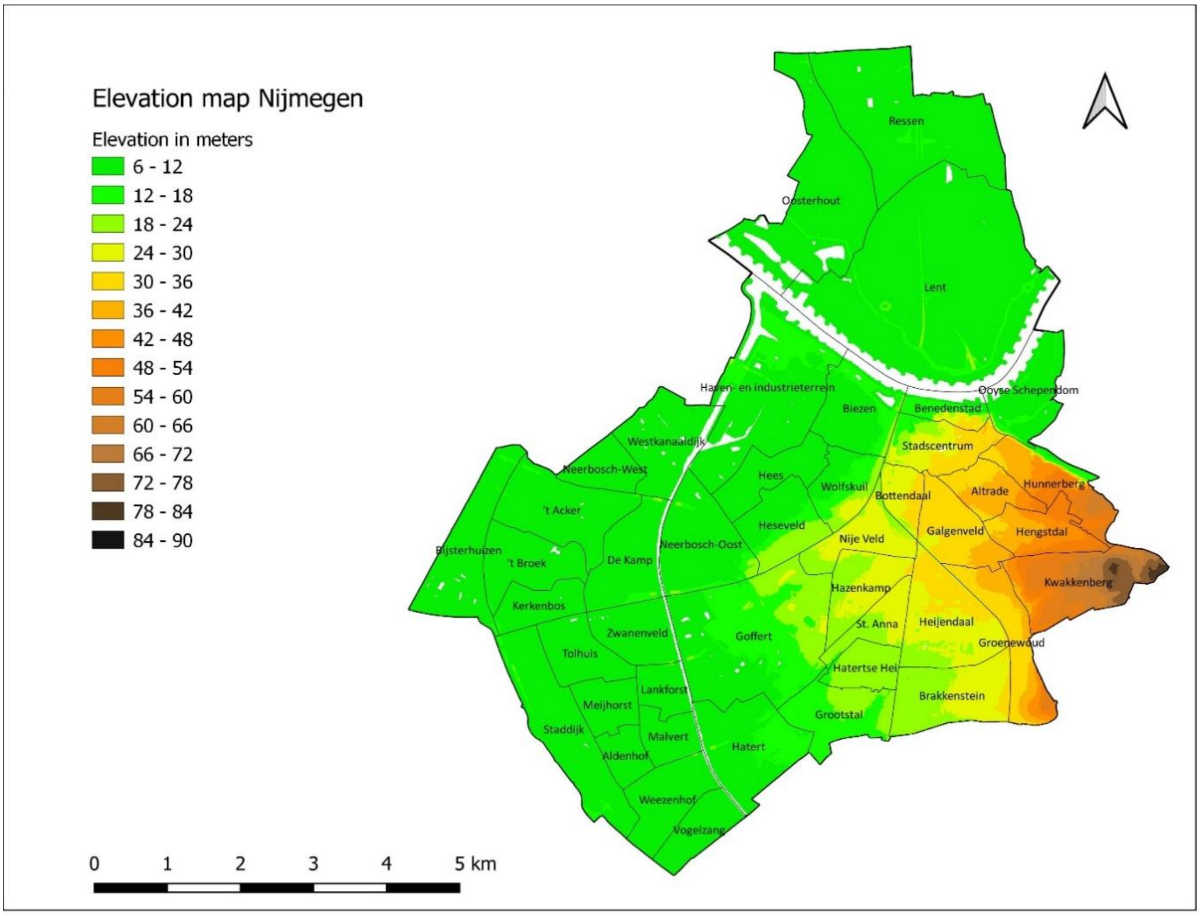

Figure 4.1: Map showing elevation in Nijmegen including neighbourhoods

4.1.2 Demography

The municipality of Nijmegen counted a total of 177.356 inhabitants, as of the 1st of January 2021; 48,5% of the population is female and 51,5% is male (Gemeente Nijmegen, 2021). Historically, Nijmegen has been home to many students since the city's university was established in 1923.

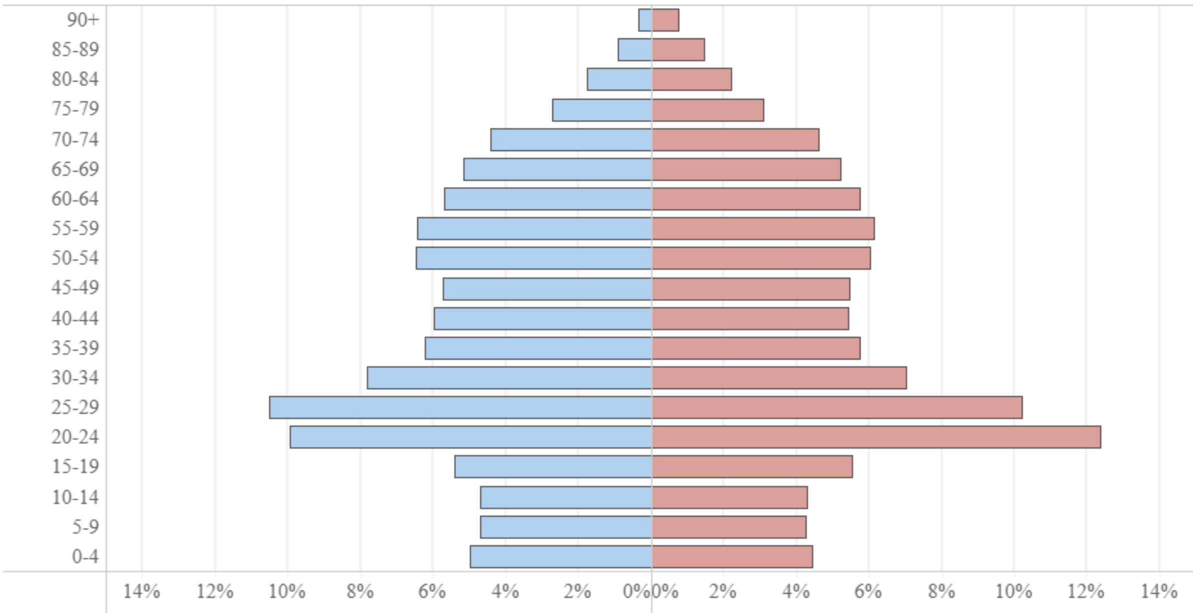

Figure 4.2: Division of age classes in percentages of total population. The red bars are women and the blue bars are men. (Gemeente Nijmegen, 2021)

Nowadays Nijmegen has a diverse population of which the students make up a significant share. There a two main educational institutions: the Radboud university, which is the largest, and the HAN (Hogeschool Arnhem-Nijmegen). Out of all these students, 20.874 live in the city. Figure 4.2 provides more insight into the age classes of the city. As for ethnicity, Nijmegen is quite diverse as well. About 27% of the population has a migration background, of which 15% has its roots in non-western countries and 12% in western countries (Gemeente Nijmegen, 2021).

4.2 Wolfskuil

The first of two neighbourhoods that is part of the case study in this research is Wolfskuil. Wolfskuil is one of two neighbourhoods in the city district of Nijmegen Oud-West, situated just west of the city centre and central train station. The word 'kuil' in its name, literally translated as pit, refers to the significantly lower elevation than its neighbouring districts towards the east and southeast. Therefore, going to the southeast of the neighbourhood involves going up relatively steep roads. The border on the east side of the neighbourhood is demarcated by the train track running between central station and Goffert. The main access roads into the neighbourhood are the Marialaan, which forms the border in the north, the Molenweg in the west and the Wolfkuilseweg in the southwest. Wolfskuil is surrounded by the neighbourhoods of Nije Veld, Biezen, Hees and Heseveld. The neighbourhood counts 6184 inhabitants, of which 47,2% are men and 52,8% are women. Concerning the diversity of the area, it seems that it can be called more diverse compared to the municipality. Out of 32% of the inhabitants with a migration background, 22% originates from non-western countries (Gemeente Nijmegen, 2021).

The first housing in the neighbourhood was built in the late 19th century, northeast of the Nieuwe Nonnendaalseweg. Most housing dates back to the first half of the 20th century. Just after the second world war, the whole neighbourhood was renovated. The majority of housing is for rent and owned by housing corporations. When looking at the social-economic status of the population, the number of households with a low income stands out, which is 60% as opposed to 9% of households with a high income. The percentage for households that have to get by with the social minimum or less is 12% (Centraal Bureau voor de Statistiek, 2018).

4.3 Nije Veld

The second neighbourhood that is part of the case study is Nije Veld, which is more commonly known as Willemskwartier, although this is just the biggest part of Nije Veld. The neighbourhood is part of the larger district of Nijmegen-Midden. It is formed as a triangle, wedged between the two train tracks that split up at the central station and that mark the borders of the neighbourhood east and west. On the south side, the Groenestraat is the most important access road. Nije Veld is surrounded by several other neighbourhoods: Bottendaal in the northeast, a bit of Galgenveld and Heijendaal in the east, Hazenkamp in the south, Goffert and Heseveld in the southwest, and of course Wolfskuil in the northwest. Regarding population size and composition it can be compared to Wolfskuil, as it counts 5571 inhabitants. The percentages of men and women and inhabitants with a migration background are pretty much the same (Gemeente Nijmegen, 2021).

Much like Wolfskuil, most of Nije Veld has come into being in the first half of the 20th century. Since the 1990's, many buildings east of the Willemsweg have been demolished and gave way to new housing, as part of restructuring the neighbourhood. The socio-economic status of the population is similar to that of Wolfskuil, with 65% low income households and 15% households on or under the social minimum (Centraal Bureau voor de Statistiek, 2018).

4.4 Policy regarding active mobility

The condition and developments with respect to the urban mobility in Nijmegen are subject to the mobility policy that the municipality wants to pursue. The policy regarding mobility in the city has been established in a special ambition document over the course of eleven years, from 2019 to 2030. 'Nijmegen goed op weg' is a building block for the larger environmental vision (Omgevingsvisie), that includes the physical environment as a whole. Every municipality is responsible for developing its own environmental vision, as part of the environmental act and as successor to the structure vision. It includes the quality and state of the physical environment as it is now, the intended and envisioned quality and state in the future, and the accompanying policy to achieve this vision (VNG, 2018).

Figure 4.3: Map showing an overview of Nijmegen's mobility vision (Gemeente Nijmegen, 2020).

The environmental vision of Nijmegen acts from 2020 towards 2040 and is themed 'City in motion'. The document revolves around four major challenges: attractive city, sustainable city, economical resilient city, and social and healthy city. Every aspect of the physical environment, including urban mobility, is envisioned using these four pillars. In the last decade, large investments have been made in order to realise infrastructural projects for every form of transport. Some examples are the new bridge in the west, the new train stations in Lent and Goffert, underground parking for cars and bicycles in the centre, several fast cycling routes and buses on green gas. Other, smaller investments have been made to improve and better connect cycling lanes and routes (Gemeente Nijmegen, 2019, p. 5-7). It is evident that active mobility has been and remains to be very important within the municipality's policy and vision.

One of the main objectives was, and still is, a decrease in car traffic within the s100, which is the ring road just east of the canal. Realising the new bridge has led to a decrease in traffic in and around the centre, but this will not be the case in 2030 if policy would stay the same. Concerning short trips up to 7,5 kilometres, it shows that many of these are done by bike or on foot (40,1% and 27,4%), but 30% is still done by car. Furthermore, the central station and Heyendaal station will be redeveloped, bearing in mind the accessibility by bike and on foot, as these movements are most (space)efficient. On a regional level, a cycling vision has been developed. This document is focused on improving the cycling network rather than expanding it. It includes the quality and width of cycling lanes, new connections to other routes and new e-hubs (e-bikes and e-scooters), more parking facilities, stimulating the use of the bicycle and a new fast lane between Arnhem and Nijmegen, through Elst (Gemeente Nijmegen, 2019, p. 19-22). Neighbourhoods on the outskirts of the city are often less accessible by bike or on foot, which is the case in Dukenburg, Lindenholt, Hatert and Neerbosch-Oost. Inhabitants face more barriers between their neighbourhood and the city centre, like the s100, the canal and greater distance in general. The mobility policy includes stimulating active mobility and improving social cohesion between these neighbourhoods by offering higher quality cycling routes, shared mobility and making public space more attractive (Gemeente Nijmegen, 2019, p. 47).

5. Research Results

In this chapter, the research results are presented, explained and analysed. Simultaneously, the sub-questions are answered in the same order as they are presented in the first chapter. Hence, the first part of the results elaborates on the GIS analysis in QGIS and the resulting measured bikeability. The second part focuses on the analysis of the survey data. The bikeability and the ranking of the components as they were perceived by the respondents are then compared to the results from the GIS analysis. This is followed by an extra GIS analysis that takes new weights for components and other potentially important factors into account.

5.1 Measured bikeability

The measured bikeability for the city of Nijmegen is determined by using the bikeability index, as it has been discussed in the theoretical framework. However, in order to make the index more suitable for the Dutch context, an adapted version with indicators that have been operationalised in a different way has been used for the GIS analysis. Before the bikeability could be determined, each indicator requires its own analysis accompanied by a map with the result, visualizing the score of this indicator for the whole of Nijmegen. The scores for both neighbourhoods are discussed and compared per component. A more detailed description of the applied techniques in QGIS are included in the appendices.

5.1.1 Quality of cycling infrastructure

Cycling infrastructure is one of the most important determinants of cycling. The quantity of cycling infrastructure in Dutch cities already is at a high level. It’s possible to ride your bike basically anywhere in the city, which makes this factor redundant for analysis.

Figure 5.1: Four types of cycling facilities: street without cycling facility (top left) (Van Bergen, 2017); street with marked cycling lane (top right), separated cycling lane (bottom left) and street especially for cyclists (bottom right) (SWOV, 2020).

The quality of the infrastructure on the other hand, is a more interesting and diverse factor. The quality can be measured in terms of surface material; is a road paved or unpaved? Another facet of quality can be safety or space; the width of a cycling lane can contribute to the overall quality. For this analysis of quality, the type of cycling lane has been used as indicator, which simultaneously indicates the level of separation from motorised traffic. This choice is based on the availability of the necessary data and explanatory power for safety and quality in general. The four types of cycling facilities are distinguished and depicted in Figure 5.1: normal streets without facilities for cyclists, marked cycling lanes, separated cycling lanes and streets especially arranged for cyclists.

In order to conduct this analysis, a data layer with all suitable roads and a data layer with separate cycling lanes and routes were downloaded and imported in QGIS. These have been merged to create an overview of all possible cycling routes in the municipality of Nijmegen. This was followed by a 'manual' analysis of all these roads, as data for the distinction of these four types didn't exist yet. By using cycling lane designations in Open Street Map and inspecting roads in Google Streetview, every piece of road was assigned a value. Every cyclists' street was given a value of 10, every physically separated lane a value of 7, all marked lanes a value of 5, and every remaining road was assigned a value of 2. The resulting map of the first part of the analysis can be seen in Figure 5.2.

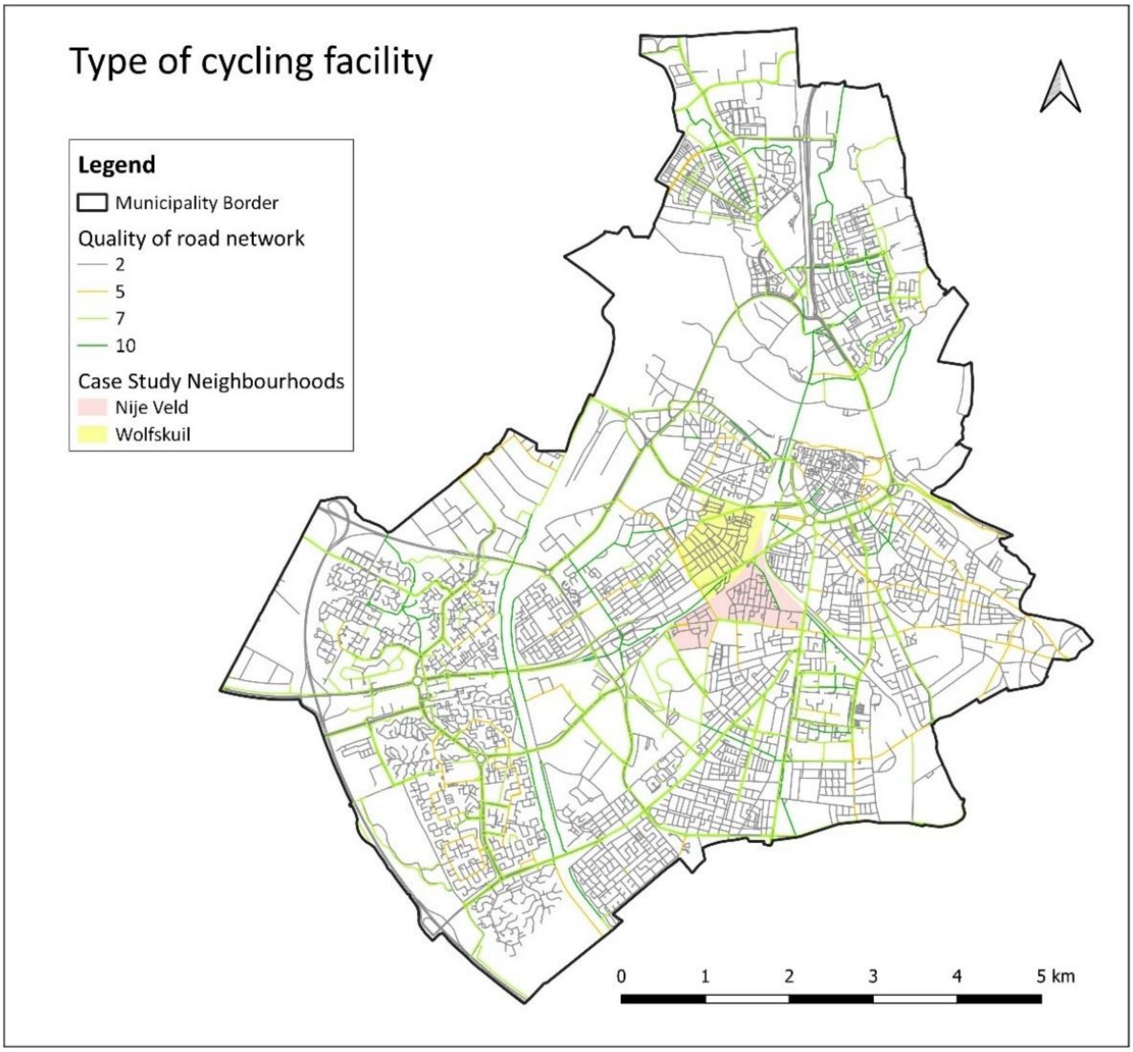

Figure 5.2: Four different cycling facility levels of the road network in Nijmegen.

The pink and yellow areas on the map represent the neighbourhoods of the case study. Many of the roads that have at least some level of separation for cyclists are main roads or roads that connect different parts of the city. The abundance of lines in the whole road network makes the map somewhat confusing and unclear. In order to give a better visual representation of the locations of the best cycling routes, the output in Figure 5.2 has been rasterised. The raster is less cluttered than a bunch of lines and makes it possible to combine this component with the other components later on. The output of the raster is depicted in Figure 5.3.

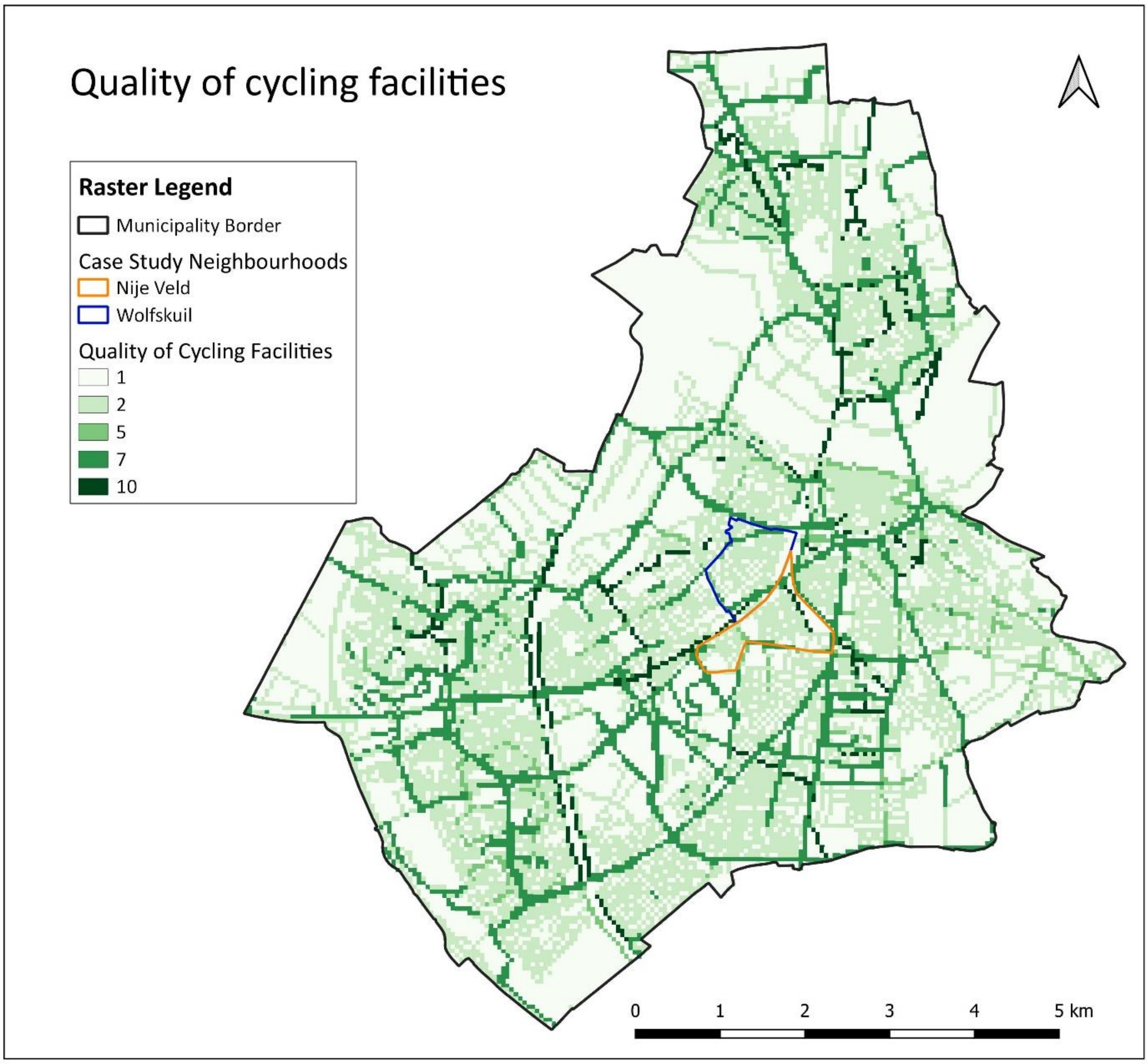

Figure 5.3: Quality of cycling infrastructure as raster output. Areas without roads have a score of 1.

Because the raster needs to cover every pixel of the municipality and the eventual bikeability score ranges from 1 to 10, all spaces without roads have been assigned a score of 1. The vast majority of the network has a score of 2, which means that these roads don't have special facilities for cyclists. Among the roads that do have cyclists' lanes, the physically separated lanes are most common, while cyclists' streets and marked lanes are more sparce. Roads with cycling lanes are distributed across the whole city, with few exceptions on the edges of the municipality. Zooming in on Nije Veld and Wolfskuil, it appears that most major roads on the edges of the neighbourhoods have lanes for cyclists. In Nije Veld, a cyclists' street connects two main roads. Apart from this, there are no cycling routes that stand out compared to other neighbourhoods. The quality of roads has been calculated as average road density per area, weighted for the score of the roads. On a scale of 0 to 1, the whole municipality has a mean density of 0,46. Wolfskuil and Nije Veld respectively have a mean density of 0,62 and 0,59, which implies that the road network of Wolfskuil is slightly denser and/or has an overall higher quality.

5.1.2 Connectivity of cycling network

The second component that has been used to measure the bikeability of Nijmegen is the connectivity of the road network that is suitable for cyclists. A well connected network of streets or route is beneficial for cycling, especially for cycling trips with a utility purpose like commuting, as good connections make for quicker journeys (Yang et al., 2019). As connectivity is a somewhat vaguer concept than quality of infrastructure, measuring can thus be done in different ways. The bikeability index by Winters et al. (2013) uses the density of intersections for this purpose. This makes sense for a grid-like network, but less for a more organic network like the roads in Nijmegen, as is explained in paragraph 2.5. Instead, this analysis is based on space syntax. To be more specific, a segment analysis has been conducted measuring, among others, integration of the full road network. Each segment of road (a piece of road between two junctions or a junction and a dead end) was analysed for its location relative to all other segments, taking into account the total number and degrees of turns necessary to reach the other segments (Hillier, 2008). The output of this analysis was transferred to QGIS and is displayed in Figure 5.4.

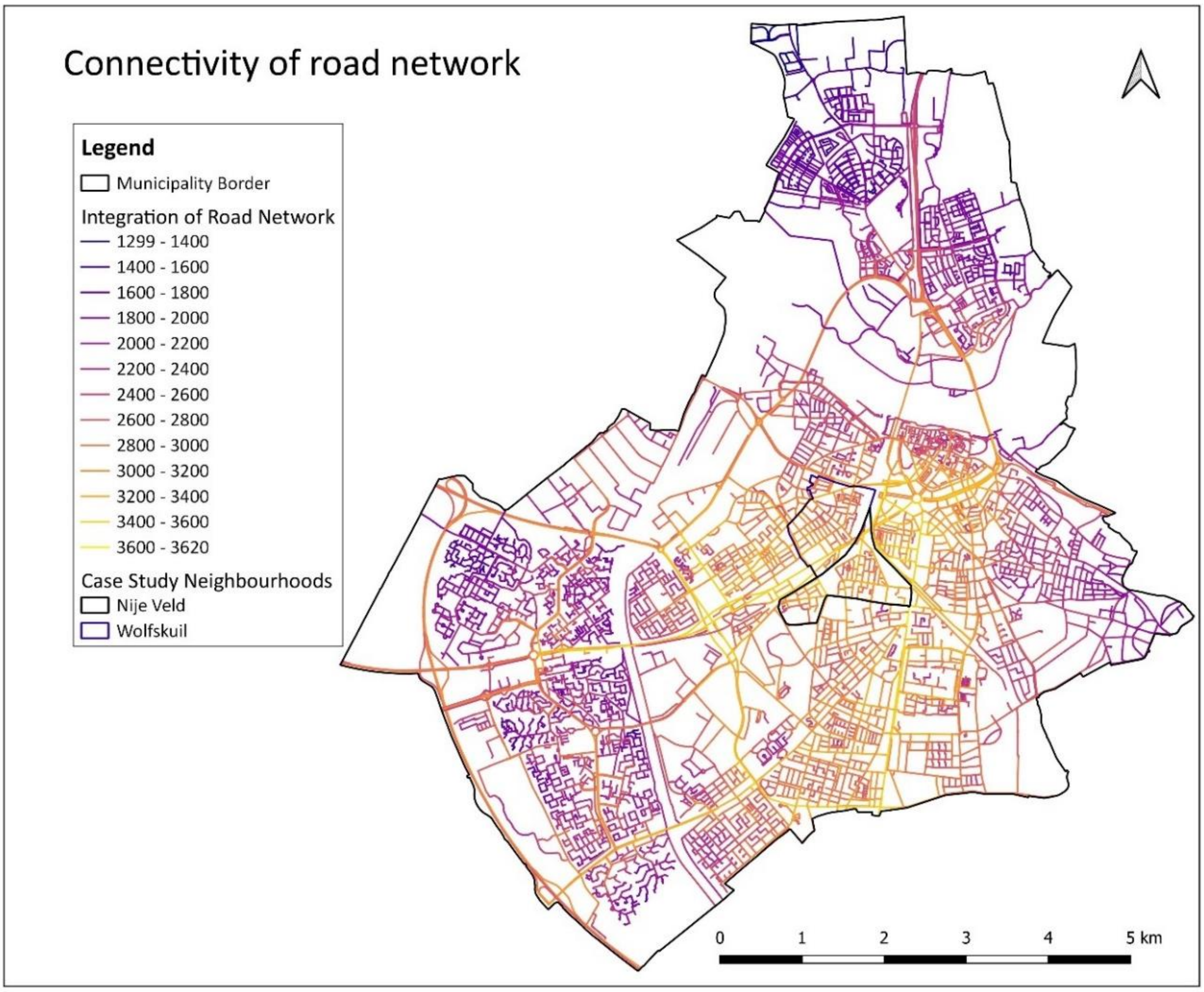

Figure 5.4: Integration (connectivity) of the road network. The values in the legend are directly derived from the analysis in depthmap.

Looking at the colour range of the map, a clear tendency is visible. The city centre and the city districts around the geographical middle of the municipality have the highest integration values, and therefore have the best connectivity with the rest the city. Furthermore, the main roads that connect the city's districts provide the vicinity with a high level of connectivity. On the contrary, the large neighbourhoods west of the canal and north of the Waal have significantly lower levels of connectivity, especially those parts further away from main roads.

The connectivity has also been transformed into a raster which can be seen in Figure 5.5. Labels and borders of city districts were added to make things more clear, and the integration values were rescaled to a 1 to 10 scale. A new colour ramp provides greater visibility of the connectivity of the city's districts. The neighbourhoods of the case study are located around the geographical centre of the municipality, which ensures that connectivity there is fairly high overall. Especially along the shared border of the two neighbourhoods, connectivity is found to be extra high. The differences in connectivity between the case study and the city are also displayed as area statistics in Table 5.1. Based on these statistics, Nije Veld is slightly better connected than Wolfskuil. Also, without the districts on the other side of the Waal and the canal, the city's connectivity improves significantly.

Statistic / **Area**	Minimum	Maximum	Mean	Standard Deviation	Range
Nijmegen	1	10	5,6	2,06	9
Inner city*	1	10	6,9	1,47	9
Wolfskuil	5,8	9,9	7,8	0,86	4,1
Nije Veld	5,8	10	8,2	0,77	4,2

Table 5.1: Connectivity statistics

**The designation 'inner city' excludes the districts Lindenholt, Dukenburg and Noord and the neighbourhoods Ooyse Schependom and Hatert.*

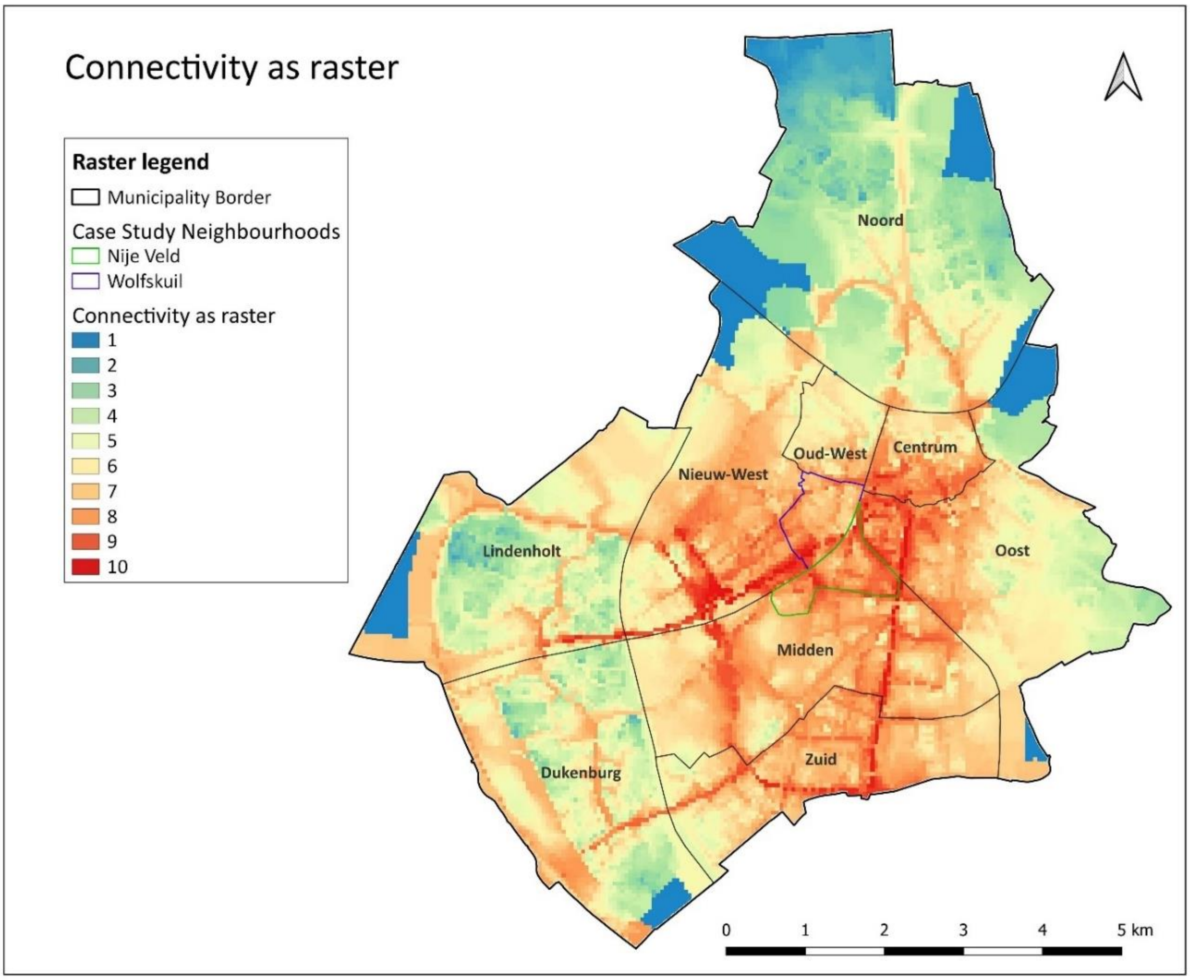

Figure 5.5: Rasterised output of the connectivity in Nijmegen. Parts of the map without roads were filled using the nearest available data. The remaining areas with no data were appointed a score of 1 and appear blue on the map.

5.1.3 Density of destinations

The next component of bikeability that has been analysed is the destination density. This component stems from the factor of land use, and especially mixed land use, as it is has great explanatory power over cycling behaviour (Ton et al, 2019). Specifically access to (a mix of) non-residential destinations is of importance for transport by bike (Yang et al, 2019). If there are no destinations nearby that can be easily reached by bike, it is less likely that one will use the bicycle often. This analysis has measured the density of every major destination category in the whole municipality. The resulting heatmaps have then been combined to find out to what extent land use is mixed in the municipality of Nijmegen. First off, the heatmaps for every destination category are briefly discussed. To determine the density, a choice regarding the reach of influence of every point has to be made. For this analysis every destination has a 1 kilometre influence-radius. Figure 5.6 features the heatmaps of destinations in the education and health care categories. Education includes all buildings that are part of a school or university. There is one major hotspot that stands out on the map; this is the campus area in Heyendaal where the Radboud university and the university of applied sciences (HAN) are located. Most other points on the map are elementary schools and high schools, as these are spread across the whole municipality. On the right side of Figure 5.6 every point represents a health care institution. Besides hospitals and clinics, general practitioners and therapists are included as well. In this case there are two major hotspots, that happen to be the two hospitals in Nijmegen. The Radboud hospital is located on campus; which explains the same hotspot as for education, and the Canisius Wilhelmina hospital (CWZ) is located in the Goffert neighbourhood.

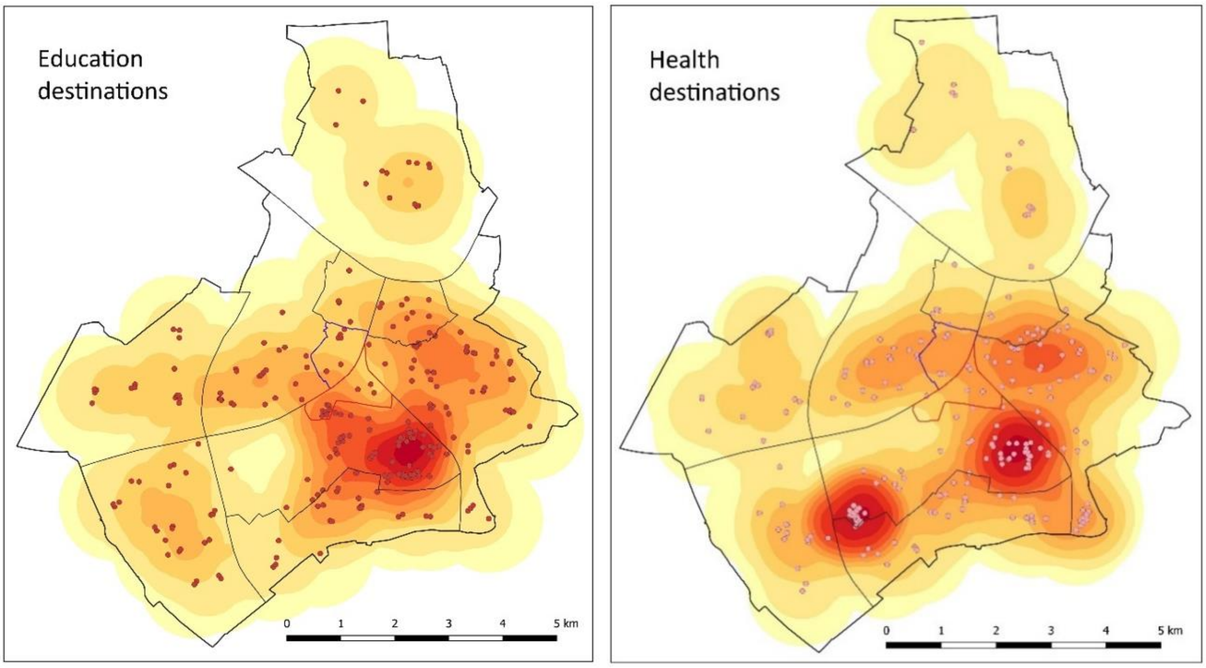

Figure 5.6: Education and health care destinations. Every point represents a single destination.

The next two destination categories are lodging and offices and workplaces, displayed as heatmaps in Figure 5.7. Lodging includes all locations where it's possible to stay overnight, like hotels, campsites, pensions, etcetera. The heatmap shows two hotspots, one of which is obviously the city centre. Most hotels are located in and around the city centre for tourists and other visitors. The other hotspot is located in an odd corner of the municipality.

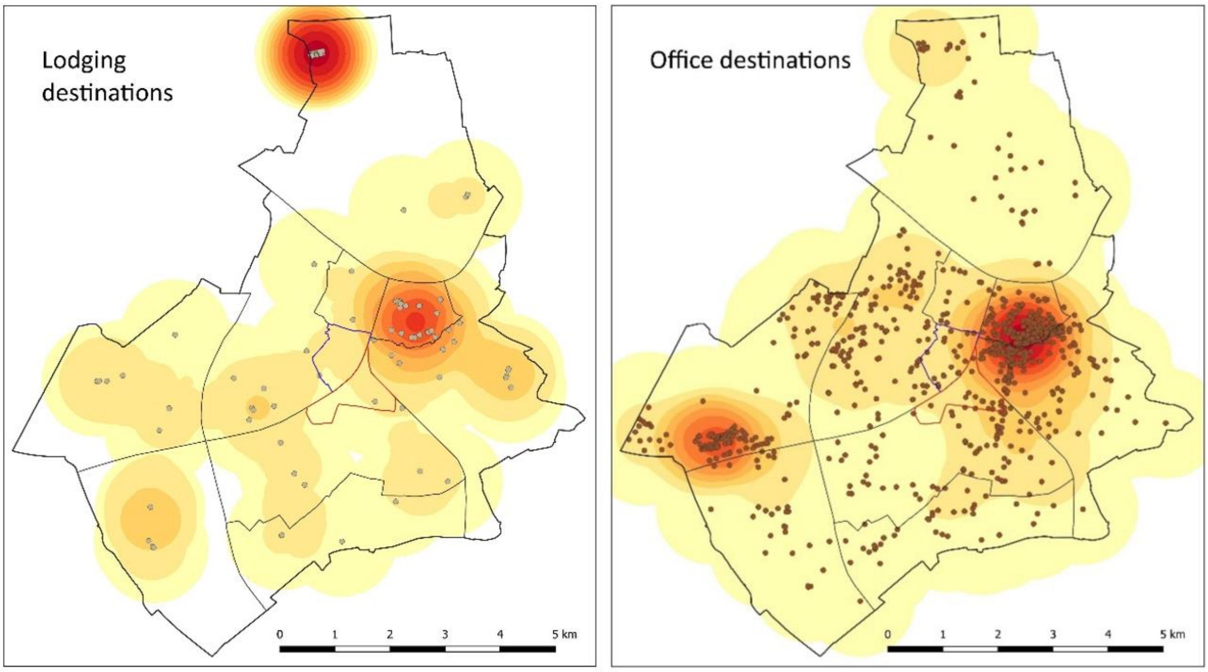

Figure 5.7: Lodging and office destinations. Every point represents a single destination.

The high density and location is caused by a chalet park, in which every chalet is marked by a point. As a consequence, this map is slightly distorted, certainly as locations for lodging are more sparse. Office destinations have been mapped on the right side of the map. Most (parts of) buildings that are being used as a workplace only are considered an office. Once again, there are two major hotspots visible. A large number of offices is concentrated in and south of the city centre, as most employment is located there. The other concentration can be found in the Kerkenbos neighbourhood in Dukenburg, where a large business and industrial park is situated.

Figure 5.8 features two heatmaps containing destinations that fall under public buildings and horeca, and sports destinations. Not only restaurants, bars and cafes are included, but theatres, libraries, community centres and the town hall too fall in this category. The vast majority of these destinations can be found in the city centre and the concentration of destinations gradually decreases while moving further away from the centre. On the other side, destinations associated with playing sports are shown. In contrast to most other heatmaps, there seem to be several major hotspots. However, this heatmap gives a slightly wrong impression, because most points are scattered across the whole municipality, not forming any undisputable hotspots. Therefore, small and possibly coincidental concentrations form bright red areas. That being said, the concentrations in the southwest of the city can be attributed to the several sports clubs located in and around large parks.

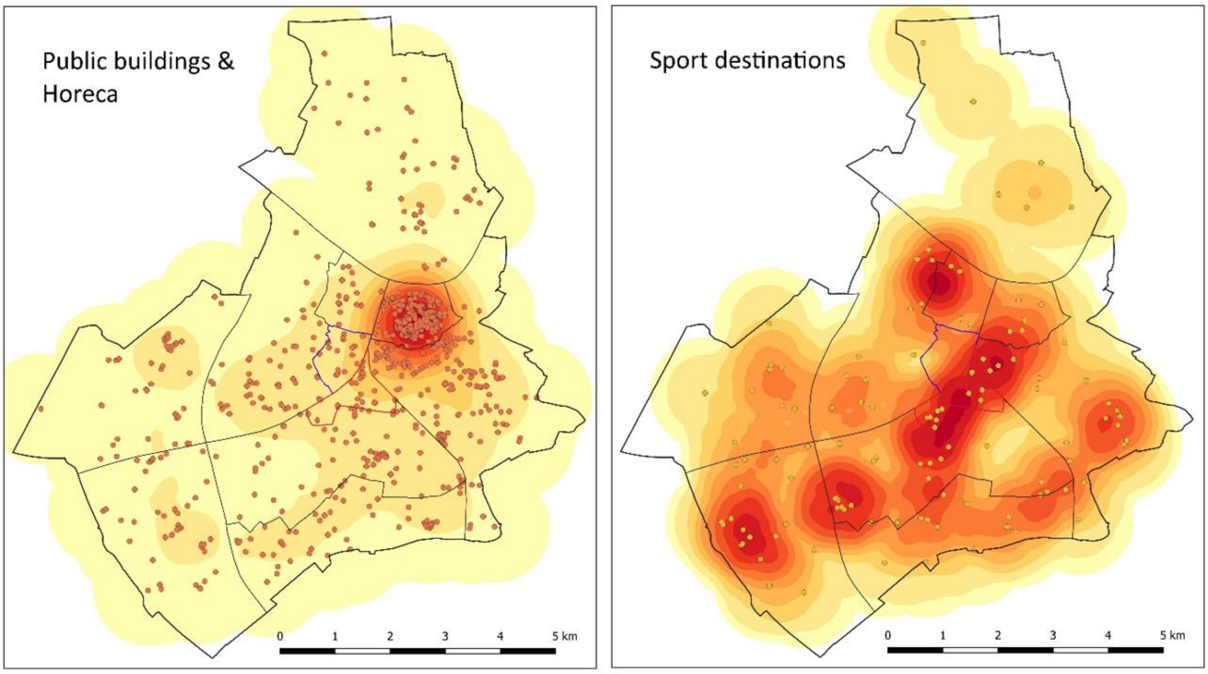

Figure 5.8: Public buildings & horeca, and sport destinations. Every point represents a single destination.

The last destination category is visualized in the heatmap in Figure 5.9. Every point in this map represents a supermarket, store or shop. As can be expected, the city centre forms one great hotspot with many large and small stores. The neighbourhoods around the city centre also boast a relatively large number of stores, as the red spot spreads over these areas. In the city districts across the canal and the Waal, the only concentrations are small shopping centres.

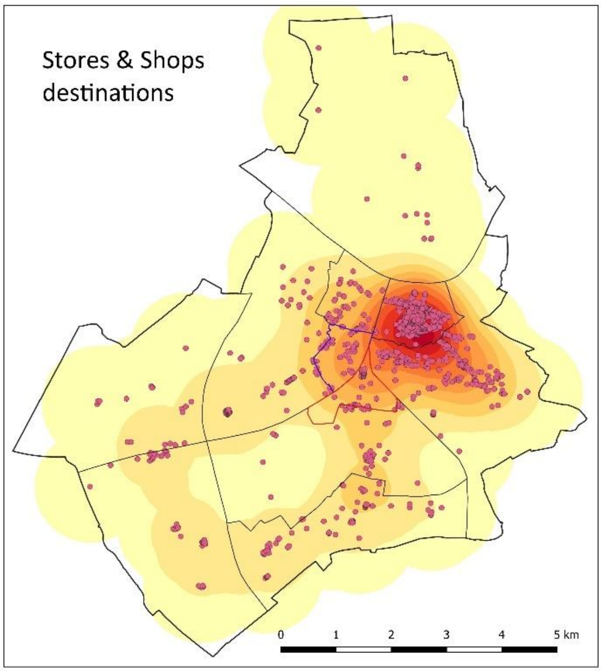

Figure 5.9: Stores and shops destinations. Every point represents a single destination. Due to the very large number of points in the city centre, the points outside the centre were assigned triple weight to visualize concentrations in other parts of the city.

After the density per destination category was visualized, the heatmaps have been merged by using a tool called 'raster calculator' to create an image that combines all of the seven destination heatmaps. The result of this analysis can be seen in Figure 5.10. Every destination category was assumed to be equally important and thus was applied the same weight. Layers with city district borders and neighbourhood borders with labels have been added to provide insight into which parts of the city have the best mixed land use. On first sight, the concentration of destinations in the city centre stands out, with the whole neighbourhood being orange and red coloured and having a mean density score of 8,18. This result was to be expected, as the concentrations of stores, horeca, and offices are the highest in the centre. The surrounding neighbourhoods all have high scores as well, as these are close to the destinations in the city centre and have many of their own amenities. Density scores are significantly lower towards the edge of the city. Besides the city centre, there are some other areas with higher concentrations of destinations. The campus neighbourhood of Heyendaal is one of these, as well as the former village of Hees, the north of Hatert, Meijhorst and its surrounding neighbourhoods, the former village of Lent and the far northwest in Ressen and Oosterhout. Based on destination density, these areas can be called more bikeable. There also are some areas with a much lower density. The Goffert neighbourhood stands out the most, being a blank spot on the heatmap. This can be explained by its land use, as half of this neighbourhood is a park and the other half is primarily a business/industrial park. The case study neighbourhoods are located close to the centre, therefore these have a fairly high destination density score. Wolfskuil has a mean density of 4,47, while that of Nije Veld is 4,75, making it slightly better situated within the city. In Table 5.2 every mean, minimum and maximum score per destination category for both neighbourhoods are displayed. The municipality as a whole and the inner city are also included for comparison.

Statistic / Destinations	Minimum	Maximum	Mean
Nijmegen			
Education	1	10	2,71
Health care	1	10	2,90
Lodging	1	10	1,95
Offices	1	10	1,69
Public buildings & horeca	1	10	1,50
Sports	1	10	3,91
Stores & shops	1	10	1,81
Combined density	**1**	**10**	**2,83**
Inner City**			
Education	1	10	3,99
Health care	1	10	4,21
Lodging	1	8	*1,97**
Offices	1	10	2,30
Public buildings & horeca	1	10	2,19
Sports	1	10	5,49
Stores & shops	1	10	2,65
Combined density	**1**	**10**	**3,78**
Wolfskuil			
Education	3	5	3,55
Health care	4	5	*4,80**
Lodging	1	4	1,94
Offices	2	6	*2,64**
Public buildings & horeca	2	5	*2,47**
Sports	2	9	6,21
Stores & shops	3	7	*4,62**
Combined density	**3,34**	**6,58**	**4,47**
Nije Veld			
Education	3	7	*4,66**
Health care	2	6	4,17
Lodging	1	3	1,56
Offices	1	5	2,59
Public buildings & horeca	2	4	2,40
Sports	5	10	*8,58**
Stores & shops	2	6	3,88
Combined density	**3,34**	**6,22**	***4,75****

Table 5.2: Comparison of the minimum, maximum and mean destination density score of every destination category (combined) per area. These statistics have been calculated using the area statistics calculator in QGIS. The density scores per indicator have been rounded to whole numbers, as opposed to the combined density scores.
**The highest mean value per category out of the four relevant areas.*
*** The designation 'inner city' excludes the districts Lindenholt, Dukenburg and Noord and the neighbourhoods Ooyse Schependom and Hatert.*

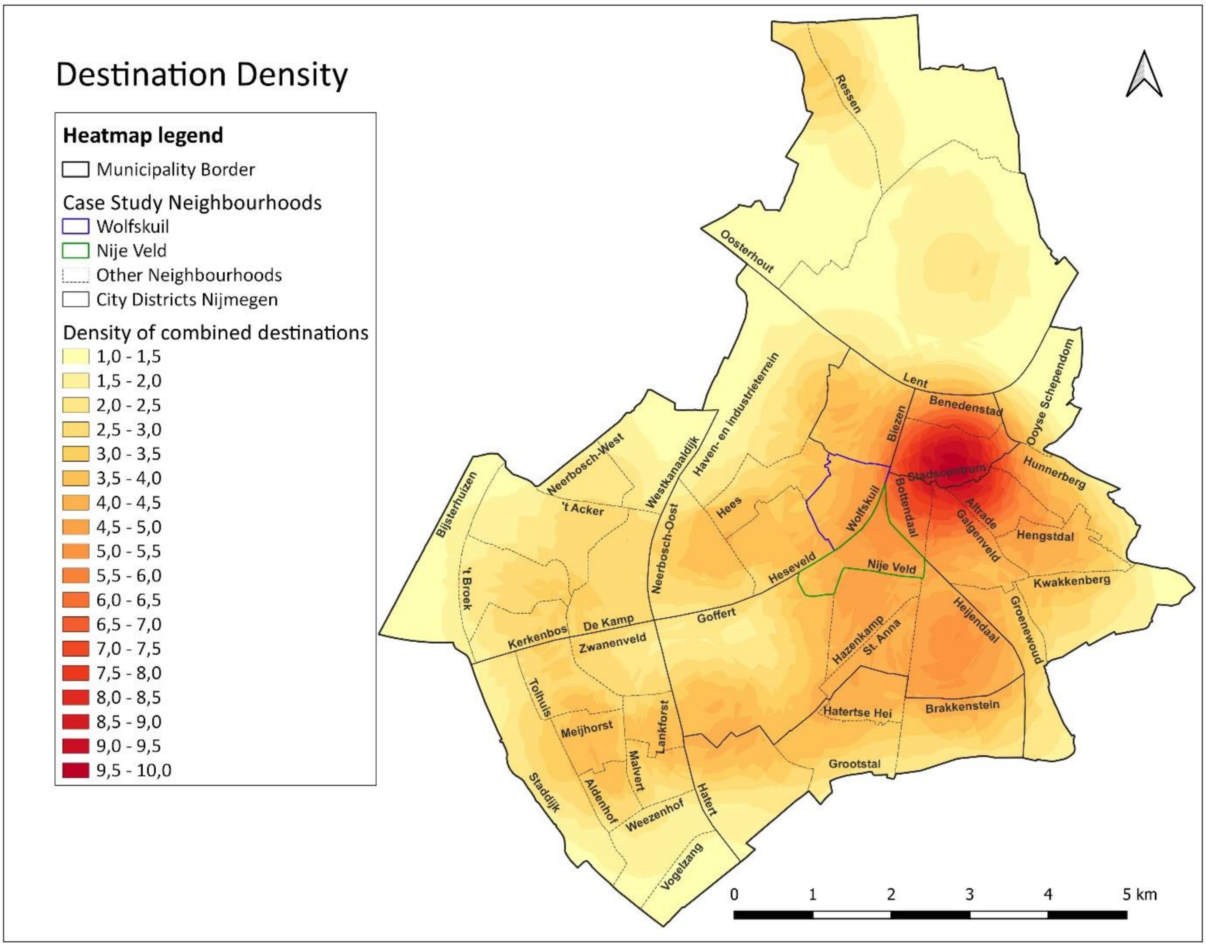

Figure 5.10: Combined destination density, including neighbourhood and district borders.

5.1.4 Elevation difference

The fourth and last component that determines the bikeability in this analysis is the elevation difference, also known as slope. The elevation in Nijmegen has already been discussed in the description of the case study and has now been analysed in QGIS to find out which parts are less bikeable, looking at the slope percentage. For this analysis, the AHN raster data accurate up to five meters has been used. In literature elevation difference plays a smaller role than, for instance, land use, but a steep hill can be very demotivating for cycling nonetheless. The results of this analysis are displayed in Figure 5.11.

In this research a completely flat surface is assigned a score of 10, while a slope of 18% or more is assigned a score of 1 (Heinen et al., 2010; Muñoz et al., 2016). An 18% slope implies that the elevation increases 180 meters for every kilometre in distance, which means it is very tough to climb by bike. A black, red and green colour ramp has been chosen, due to the significance of the red areas. Most black areas aren't relevant for bikeability, as these often represent the banks of bridges, dikes and other elevated roads. Another example of an irrelevant black area on the map is the oval just south of Nije Veld, which is the elevated Goffert stadium. This is one of the drawbacks of using a very detailed version of the AHN for measuring slopes, as it captures every piece of relief on the surface, instead of hilliness in general.

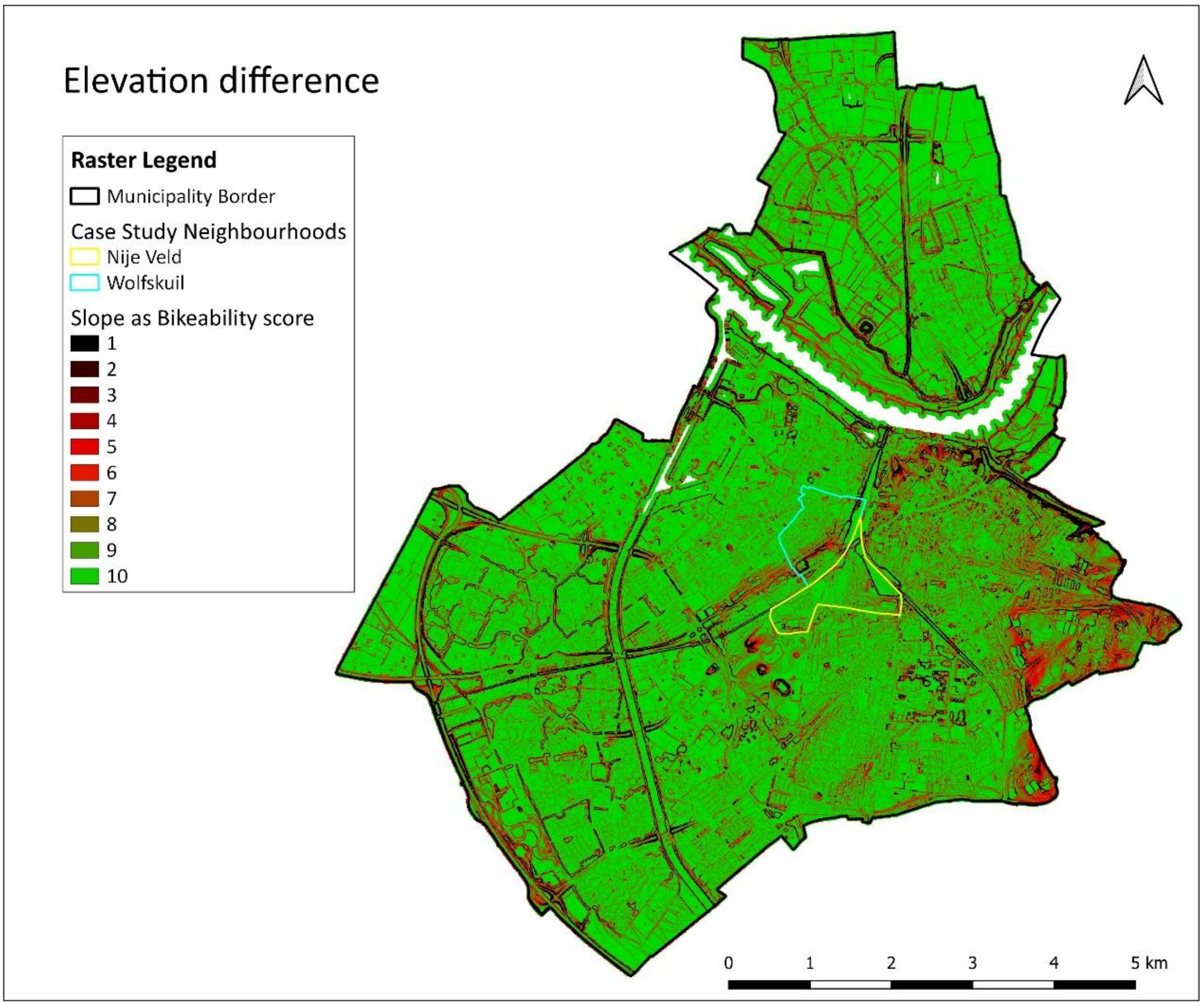

Figure 5.11: Slopes in the municipality of Nijmegen. The slope percentages (steepness) have been rescaled to a 1 to 10 scale.

The larger red areas are the most important on this map, as these indicate actual hills that can be climbed by bicycle. While focusing on these areas, the east of this city stands out the most. The elevation increases up to 80-90 meters in some places and this is reflected in the slope in this part of the city. Another important steep part is the area that stretches from the south of Heseveld to the north of Wolfskuil. In order to leave Wolfskuil by bike on the east side, one has to climb this short but steep hill. Another steep slope can be encountered when going from the city centre to the Waalkade, which is located in the Benedenstad. An honourable mention goes to the slopes that indicate an approach to a bridge or an overpass. The best examples of these can be found at the bridges crossing the canal. Unlike Wolfskuil, Nije Veld doesn't have significant slopes. In Table 5.3, general statistics of the case study neighbourhoods and the city are shown.

Statistic / **Area**	Mean Slope	Mean Score (1 – 10)
Nijmegen	3,56	8,60
Inner City	3,87	8,47
Wolfskuil	3,89	8,49
Nije Veld	3,09	8,86

Table 5.3: Mean slope and resulting mean score for bikeability

5.1.5 Bikeability index of Nijmegen

All four bikeability components have been discussed and visualized in the previous paragraphs. In order to arrive at a comprehensive visualization of the bikeability in Nijmegen, all resulting raster maps have been merged using the raster calculator tool in QGIS. This has been done by adding up all cells of every input layer and simply dividing the sum by 4. To make this calculation possible, every indicator had to be rescaled to a 1 to 10 scale, which is visible in the previous map legends. Every layer has the same weight in this first calculation, assumed to be equally important. The outcome of the calculation can be seen in Figure 5.12. The structure of this map is less close-knit than the maps per indicator, which can be explained by the differences in pixel size between the component maps. The elevation and destination density rasters consist of 5 meter pixels, while the connectivity and road quality rasters consist of 50 meter pixels. If these would be merged without adapting pixel size, the result looks just like two overlayed, half-transparent maps. In order to prevent this, the 5 meter rasters have been changed into 50 meter rasters and the 50 meter rasters have been changed into 100 meter rasters. By doing this, the map does not only appear more fluid and comprehensible, it also increases the range of influence of connectivity and quality of roads. For example, instead of only having a positive effect in the surrounding 50 meters, a well-connected road has a positive effect on bikeability within a range of at least 100 meters. With the measured bikeability being analysed and visualized, the resulting bikeability for the municipality and the neighbourhood can be described and compared.

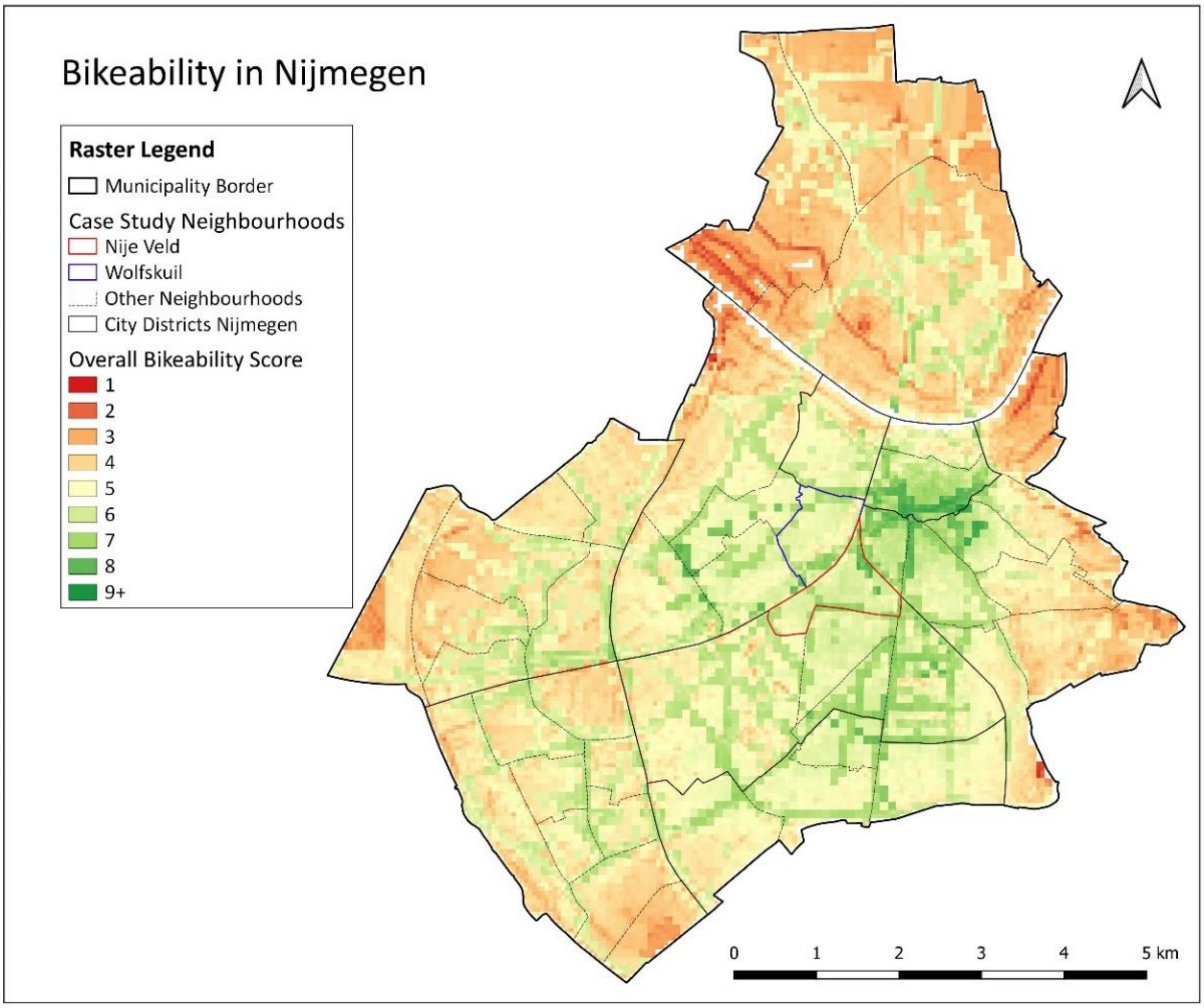

Figure 5.12: Overall bikeability scores in the whole municipality (cell size = 50 metres).

Nijmegen

Starting off with the bikeability in Nijmegen, the variation in bikeability scores across the city is something that catches the eye immediately. The highest scores (of more than 8) can be found in and around the city centre. Almost all neighbourhoods within the inner city boast high maximum bikeability scores, however, the mean scores slowly decrease moving further from the centre. In the city districts Nijmegen Noord and Dukenburg, bikeability is worse on average, as high scores mostly concentrate around major roads. The worst bikeable areas in the city are located in Oosterhout, Lent and Ooyse Schependom. It should be noted that in most of these areas there aren't many roads or paths to cycle on. The neighbourhoods in the east of the city also have significantly lower bikeability. Some characteristics of the separate components stand out on the map. For example, the very steep slopes of the dike in Oosterhout are clearly visible. Other examples are the green areas around major roads, partly due to the correlation between connectivity and quality of cycling facilities. Major roads do not only often have separated cycling lanes, but tend to have higher connectivity values as well. The map in Figure 5.12 gives a good impression of bikeability throughout the whole city. However, since cycling is only possible on designated infrastructure, it is important to find out how bikeable the cycling infrastructure network in Nijmegen is. Therefore, a bikeability profile of the road network has been made in QGIS, which is depicted in Figure 5.13. This map has more practical and societal relevance, as cyclists can base their route on its bikeability. Policy makers may use the map to analyse which roads are less bikeable and how to improve them.

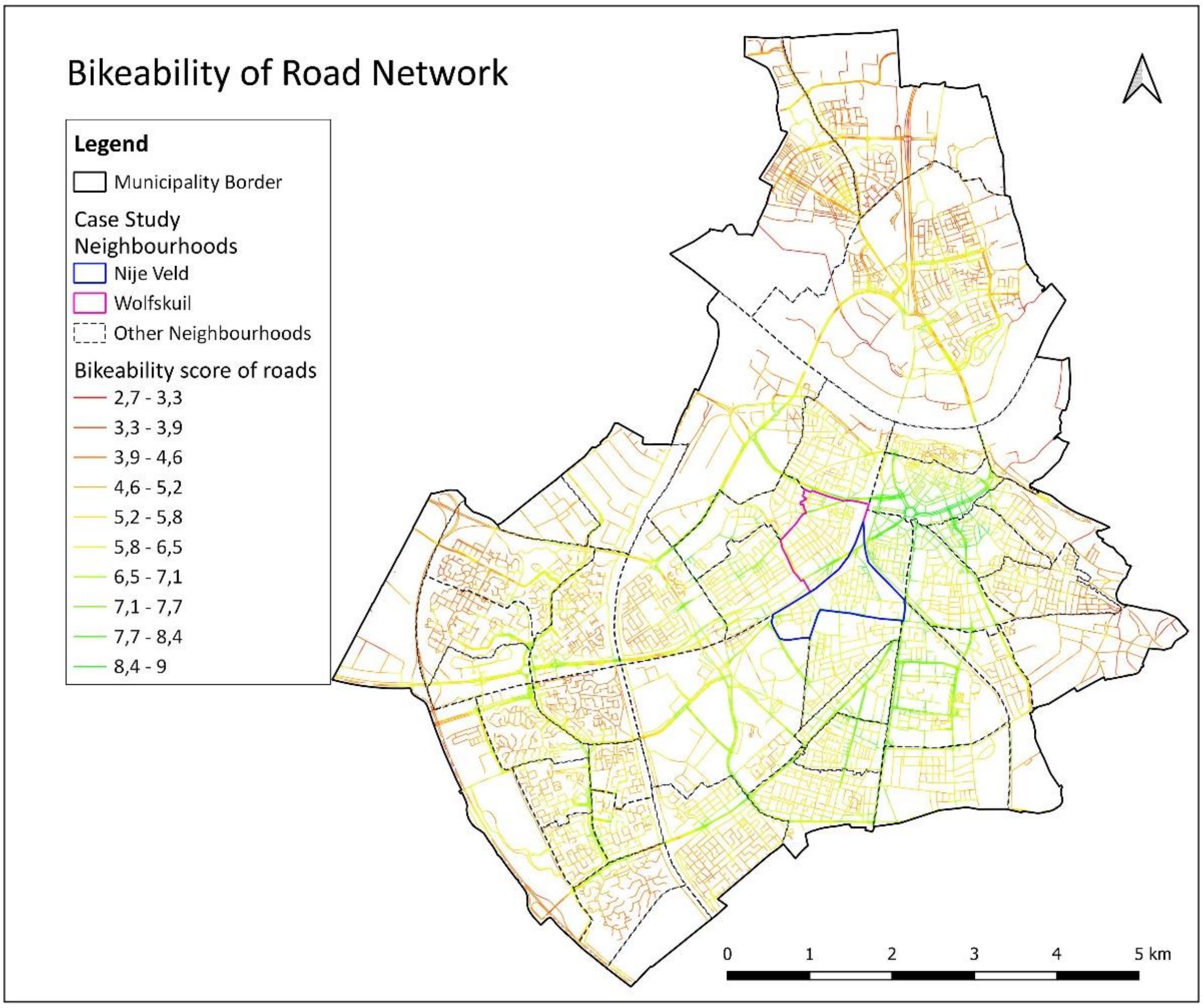

Figure 5.13: Bikeability scores of the road network, including separated cycling lanes

Wolfskuil & Nije Veld

In Figure 5.14, a map with a smaller scale showing the bikeability in the case study neighbourhoods is displayed. For this purpose, the detailed versions of the component maps, as they are presented in the previous paragraphs, have been used to calculate a close-knit raster. Differences within the neighbourhoods are clearly visible this way. The bikeability in the case study neighbourhoods is less varied than it is for the rest of Nijmegen, which is visible in the map legend that only ranges from 3.1 to 8.6. Wolfskuil and Nije Veld are both situated close to the city centre and actual middle of the city, which explains the relatively high minimum score. Regarding the low scores, it appears that most concentrate along a corridor in Wolfskuil. This happens to be the rather steep hill facing northwest that needs to be climbed in order to reach the Graafseweg and Nije Veld. Other elements in the map that stand out are the higher scores, which primarily occur where major roads with cycling facilities are situated. The road network has been laid over the map, and this shows that areas with very low scores can often be avoided, as few roads run through those areas. In Table 5.4, the bikeability statistics are displayed per area. An extensive list of bikeability statistics for every neighbourhood and city district is included in the appendix.

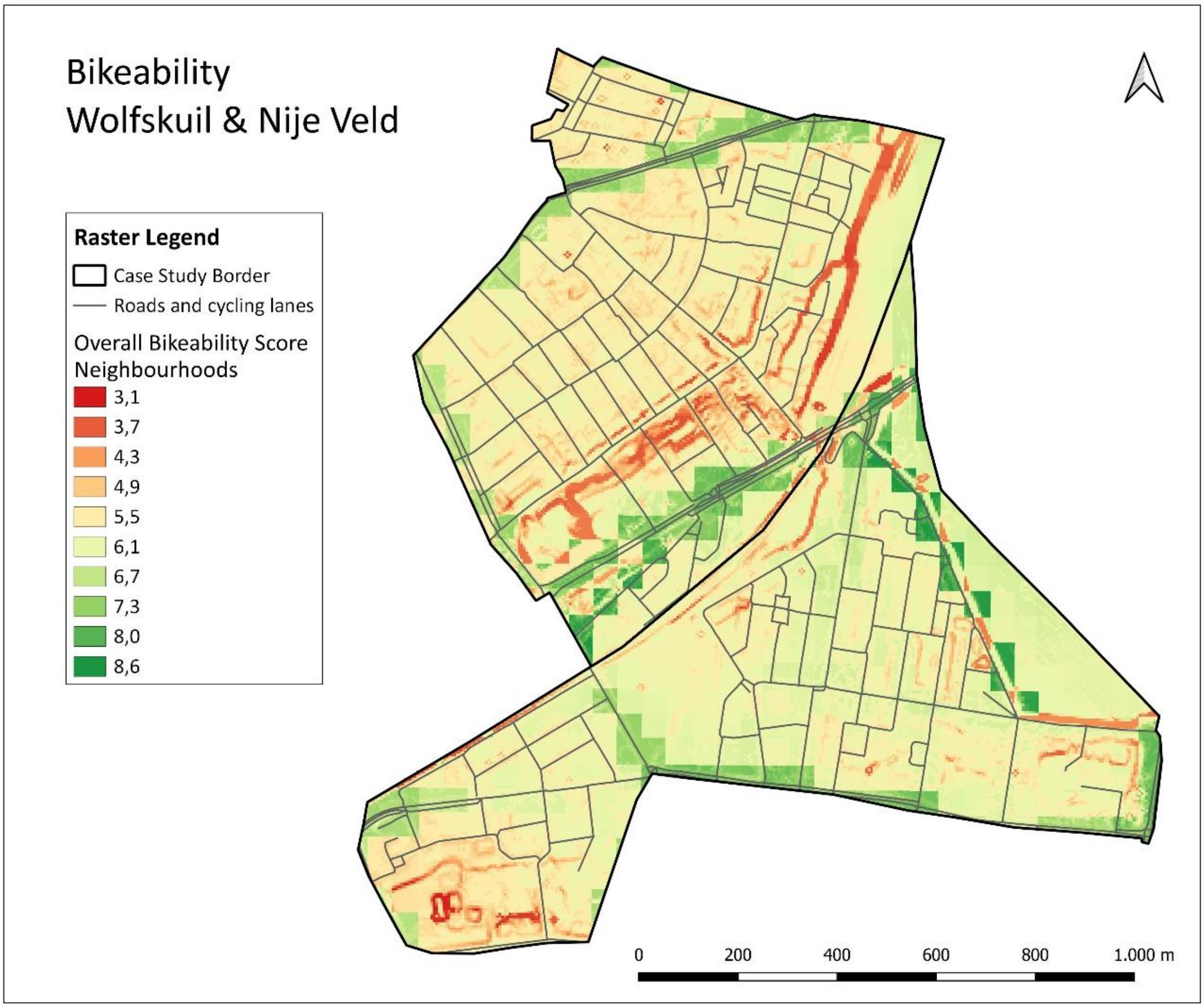

Figure 5.14: Overall bikeability scores in the neighbourhoods of Wolfskuil and Nije Veld. It concerns a more detailed version (cell size = 5 metres), which allows for a more precise overview of the bikeability on this scale.

Statistics / Area	Minimum	Maximum	Range	Mean	Standard Deviation	Median
Nijmegen	**1,35**	**9,19**	**7,84**	5,13	1,13	5,04
Inner City	1,35	9,19	7,84	5,64	1,07	5,54
Wolfskuil	4,46	7,78	3,32	6,01	**0,73**	5,77
Nije Veld	4,95	8,49	3,54	**6,27**	0,76	**6,04**

Table 5.4: Bikeability statistics per area. Highest values are in bold. The statistics are based on the raster presented in Figure 5.12.

Looking at the numbers in the table, average bikeability is best in the neighbourhood of Nije Veld, with a mean score of 6,27. Wolfskuil is a close runner-up, with a mean score of 6,01. The slightly better bikeability in Nije Veld is also reflected in the higher minimum and maximum scores and the higher median score. While the neighbourhoods are quite similar, looking at the used components, it's the elevation difference in Wolfskuil and the lack of it in Nije Veld that gives the latter the edge in its bikeability score. Compared to the other relevant areas, bikeability in the case study area is better on average, as the whole municipality has a mean score of only 5,13 and the inner city boasts a mean score of 5,64. The minimum and maximum score both are located in the inner city area. The standard deviation is significantly higher for the whole municipality, which makes sense as it includes more variety in bikeability scores.

5.2 Perceived bikeability

The bikeability in Nijmegen has been measured using publicly available data. This has resulted in an objective view of the best and worst bikeable areas in the city. This subchapter discusses the survey results and the perceived bikeability in the case study neighbourhoods and in Nijmegen. First off, the descriptive statistics of the population sample are elaborated on, as these are thereupon used as independent variables to analyse and find differences in perceptions and rankings of indicators between different groups of respondents. In the next subchapter, the ranking of components according to the respondents will then be used to apply different weights to the existing components in QGIS, taking into account extra factors provided by the respondents as well.

5.2.1 Descriptive statistics of population

The questionnaire was filled out and completed by 53 independent respondents living in one of both case study neighbourhoods. Out of all respondents, 49,1% is female and 50,9% is male. 47,2% of the respondents resides in Nije Veld and 52,8% is living in Wolfskuil. The divisions of these sample characteristics are shown below in Figure 5.15.

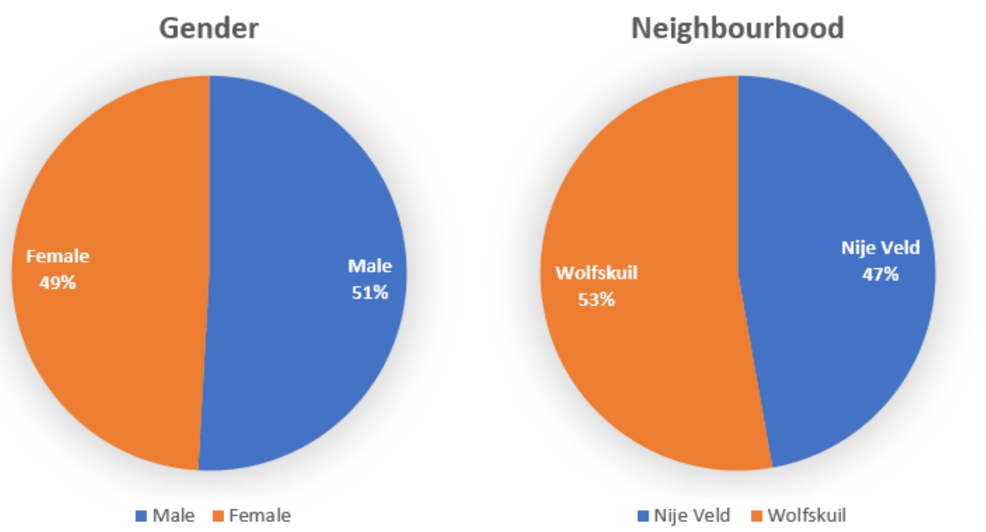

Figure 5.15: Division of gender and neighbourhood among respondents

Furthermore, respondents were asked about their age. A histogram showing the age distribution of the respondents is displayed in Figure 5.16. The youngest respondent was 14 years old, while the oldest was 74 years old. The mean age of the sample is 39,54 years and the median age isn't far off, being 38 years. The age distribution is roughly normal, but clearly there are few respondents in the 37 to 42 years category, while many more respondents in the 22 to 27 category and 42 to 47 category have completed the questionnaire. The fourth and last characteristic of the respondents, which is income group, was derived from the 6-digit postal codes of the respondents. The Centraal Bureau voor de Statistiek (CBS) has key data available for every postal code from every year. The most recent, freely accessible data set for 6-digit postal codes stems from 2017, and this data set was used to make the survey sample diverse in terms of location and income groups. To be more specific, by income the median income per household is meant. These median incomes are classified in groups of 20% or 40%, dependent on the income class they fall in (Van

Leeuwen & Venema, 2021). It goes without saying that this method is less accurate to find out the income of respondents than just asking them directly in the survey.

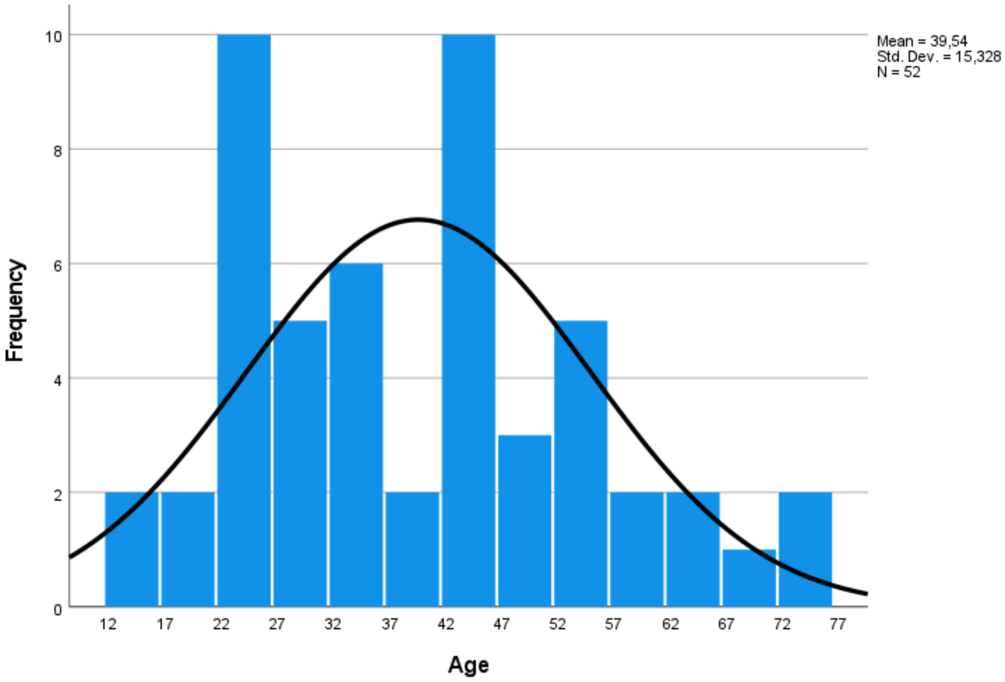

Figure 5.16: Distribution of age among respondents.

However, since income is a sensitive subject for most people, potential respondents could have been scared off by being presented with this question. This could've led to a lot of missing values or incomplete questionnaire, jeopardizing the reliability of the survey. Every 6-digit postal code where respondents filled out the questionnaire is visualized on the map in Figure 5.17. An attempt was made to visit every part of the case study to conduct questionnaires, while the variety of income groups was also taken into account. The division of the respondents' incomes is visualized

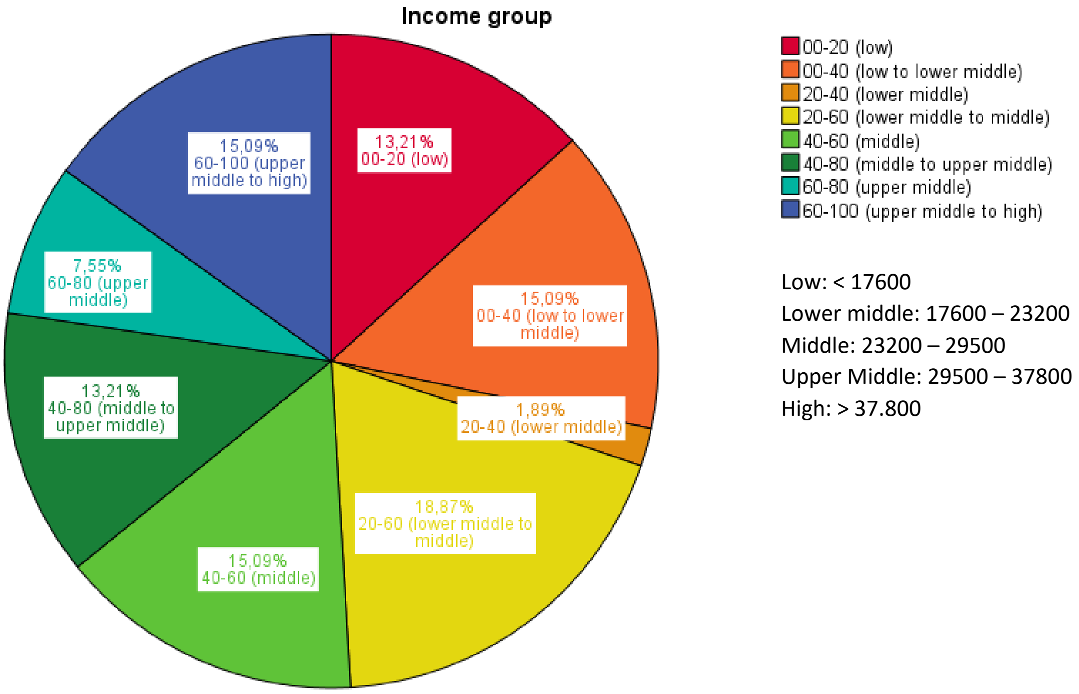

Figure 5.17: Income of respondents, based on 6-digit postal code data and categorized by CBS income groups. The frame on the right shows on which median incomes (in euros) the income groups are based.

in the pie chart in Figure 5.18. The median income group among the respondents is the middle income (€23200 – €29500). In order to make the SPSS data set more reliable and suitable for conducting analyses, two independent variables were added to the SPSS data. Income was divided into three groups: low, middle and high. Furthermore, the respondents' ages were divided into four equally large age groups: 14 – 25, 26 – 39, 40 – 49 and 50 – 74. The corresponding pie charts of both variable are displayed in Figure 5.18.

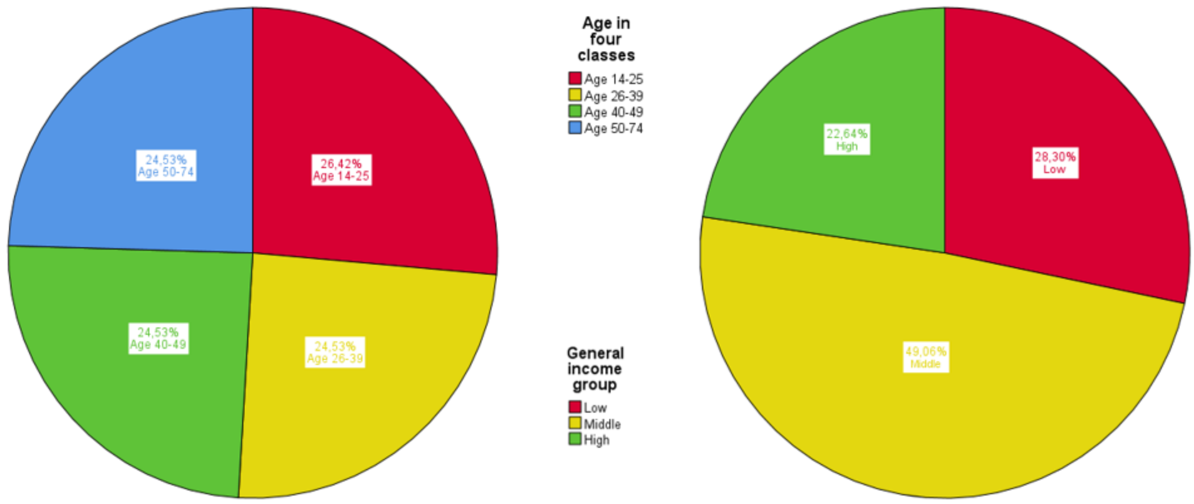

Figure 5.18: Additional variables of age in four classes (left chart) and income in three groups (right chart). Both variables are derived from the original variables of age and income groups.

5.2.2 Perception of bikeability indicators

The questions in the survey can be divided into two types; one or two questions were posed about the perception of each bikeability indicator in Nijmegen and in the respondents' neighbourhood. The remaining questions per indicator were about its' importance for cycling in general, according to the respondent. This paragraph delves into the perception questions. Every question has used a 5 point Likert scale for response options, as explained in the methodology chapter.

Quality of cycling infrastructure

The respondents were asked to what extent they agree with two statements about the suitability and safety of the roads and cycling infrastructure. One statement concerned the city as a whole, while the other concerned their own neighbourhood. The division of the responses is displayed in Figure 5.19. On first sight the road network in the whole city seems to be more suitable and safe for cycling, according to the perception of the respondents. To find out if there is a significant difference between the responses of the city and neighbourhood variables, a Wilcoxon signed-rank was carried out, using the mean ranks of the variable data. The results of the test indicated that the roads in Nijmegen (mean rank of 17,4) are indeed perceived as more suitable and safe than the roads in the respondents' neighbourhoods (mean rank of 13,0), $Z = -2{,}473$, $p = 0{,}012$, even though the medians and modes of both variables are equal. Besides comparing the two dependent variables, linear regression and non-parametric tests were used to discover possible relations between the independent variables and level of agreement with the statements regarding road safety and suitability. In doing so, one significant relationship was found, which is specified in Table 5.5. Respondents in higher income groups think of the roads in Nijmegen as less bikeable than respondents in lower income groups do. No further significant linear relations between the respondents' characteristics and the dependent variables were found.

Variable	B	95% CI	Beta	t	p
Constant	4,093	[3,685 4,502]		20,108	0,000
Income	-0,087	[-0,168 -0,007]	-0,292	-2,178	0,034*

Note. R^2adjusted = 0,067. CI = confidence interval for B.

Table 5.5: Regression analysis summary for independent variable 'income group' predicting Perceived suitability and safety of roads in Nijmegen for cyclists.

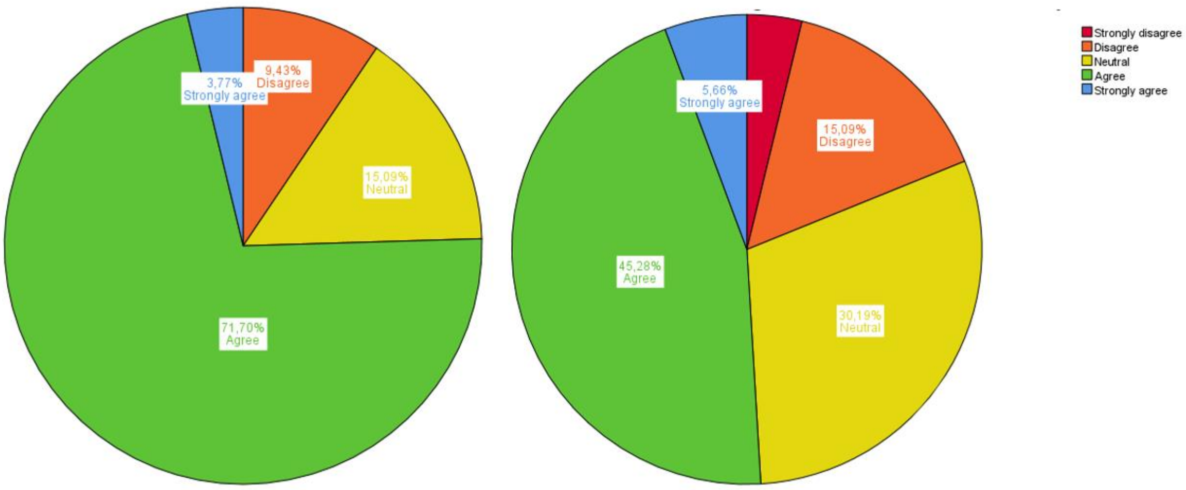

Figure 5.19: Responses to: 'To which extent do you agree with the following statement: "The roads in … are suitable and safe for cyclists.".' The left pie chart represents Nijmegen, the one on the right the neighbourhood.

Connectivity of road network

The questionnaire included two questions regarding connectivity, one about Nijmegen and the other about the respondents' neighbourhood. In Figure 5.20 pie charts showing the division of responses are included. Both questions were answered relatively positive, yet the statement about the neighbourhood elicited the most agreement, with 81,2% of the respondents choosing agree or strongly agree. Again, a Wilcoxon signed-ranks test was performed to discover a significant difference between two response categories, if any. The results of the test indicated that the respondents' neighbourhoods (mean rank of 19,3) are indeed perceived as better connected than the city of Nijmegen in its entirety (mean rank of 12,5), Z = -4,635, p = 0,000, with respective medians of 4 and 3. The two questions about the connectivity aspect were also analysed for possible (linear) relations with the sample's characteristic variables, yet this yielded no significant outcomes, so it can be assumed that every group of the population gives the same answers to these questions.

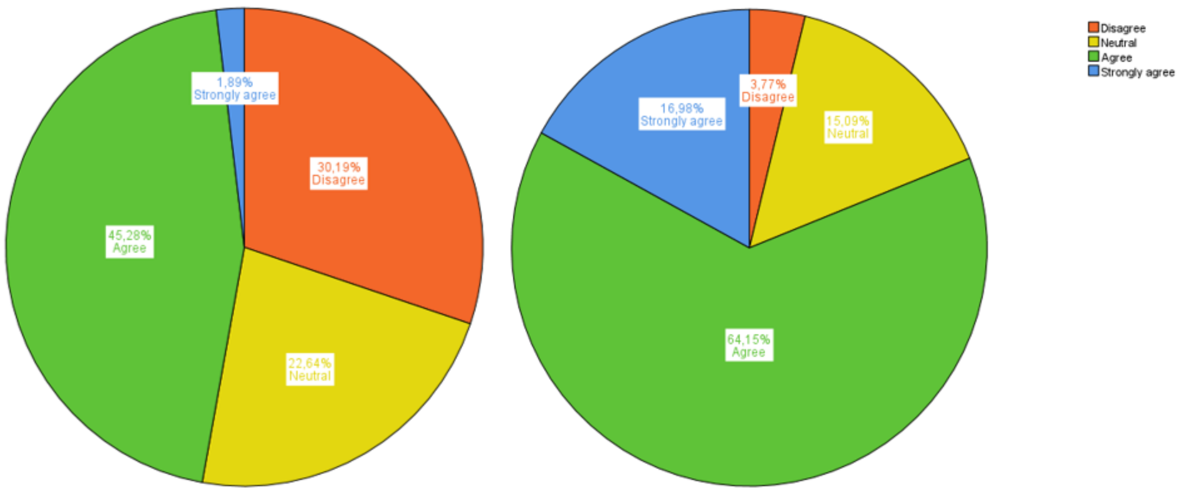

Figure 5.20: Responses to connectivity statements: 'All city districts and neighbourhoods in Nijmegen are interconnected by fast and direct cycling routes.' is represented by the pie chart on the left and 'I feel like I can reach another part of the city quickly from home.' on the right.

Destination accessibility and density

This bikeability component consists of two questions in the survey, both concern the seven destination categories that have been used in the GIS analysis. Respondents were first asked to indicate how long they would be willing to cycle at most, to reach each type of destination. Thereupon they were asked to indicate if each destination is reachable by bike, within the time given in the first question. This paragraph analyses the second question. The results of this question are given in Table 5.6. Most respondents can reach every destination within the time they're willing to cycle for. However, work stands out from the rest, as the workplace is reachable by bike for only 71,7% of the respondents.

Destination reachable?		**N**	**%**
Work	Yes	38	71,7%
	No	15	28,3%
Groceries	Yes	53	100%
	No	0	0%
Other stores	Yes	52	98,1%
	No	1	1,9%
Horeca	Yes	51	96,2%
	No	2	3,8%
Sport	Yes	50	94,3%
	No	3	5,7%
Health	Yes	51	96,2%
	No	2	3,8%
Education	Yes	52	98,1%
	No	1	1,9%

Table 5.6: Responses to 'Can you reach these destinations within the time you are willing to cycle for?'

To be sure this is no coincidence, a Wilcoxon signed-ranks test was done, comparing work with sport. The results of the test indicated that work (mean rank of 8,5) can't be reached by bike as well as sport destinations (or other destinations for that matter) (mean rank of 8,5), $Z = -3{,}000$, $p = 0{,}004$. Of course, places where respondents work can be anywhere in or outside the city, so this doesn't necessarily say anything about the bikeability of that city.

Elevation difference

The last component of the bikeability index was covered by two perception questions as well. The respondents were asked about the influence of the elevation difference on the suitability of the city for cycling. The same was asked for the neighbourhood of Wolfskuil. Nije Veld was left out of this category, due to lack of significant slopes in this neighbourhood. The corresponding pie charts of the responses are shown in Figure 5.21. The division of the answer categories seems to be roughly the same across both charts. To find out if it is the same statistically speaking, a Wilcoxon signed-ranks test was carried out. The results of the test show that there is no significant difference between the perceived effect of the elevation difference in Wolfskuil (mean rank of 12,5) and Nijmegen (mean rank of 11,2), $Z = -1{,}208$, $p = 0{,}253$, with the median, mode and range being the same for both. Both variables were checked for possible (linear) relationships with each of the respondents' characteristics, but no significant outcomes were found after the linear regression and non-parametric tests had been carried out.

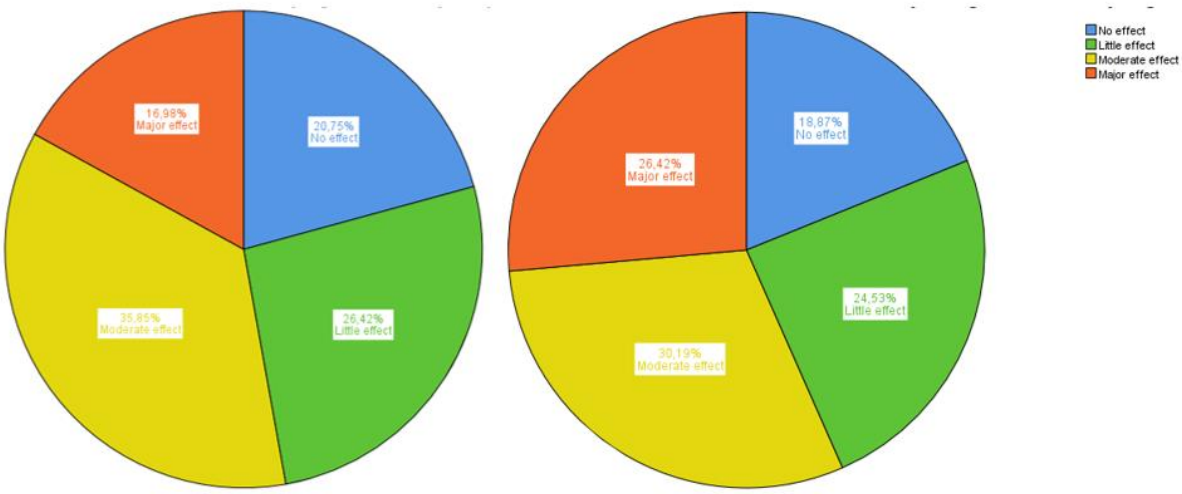

Figure 5.21: Responses to 'To what extent does the elevation difference in ... exert influence on the suitability of ... for cycling?'. The pie chart on the left represents Nijmegen, the one the right Wolfskuil.

Perceived bikeability

All four components and the way these are perceived by inhabitants of the case study neighbourhoods have now been analysed. In order to make statements about the perceived bikeability as a whole, the SPSS data output of every discussed perception-question per respondent was calculated for the average score. The scores per question were adjusted from a Likert scale to a 1 to 100 scale, in order to maximize the accuracy of the scores. The score used for the accessibility of destinations is an average of the seven destination variables, where 'no' equals a score of 1 and 'yes' a score of 100. The resulting average was divided by 10 to match the bikeability index scale. The average bikeability scores of all respondents were plotted in a histogram, displayed in Figure 5.22. What catches the eye is the division of the variable, as it follows the normality curve quite well, only excluding the low frequency of scores between 8 and 8,5.

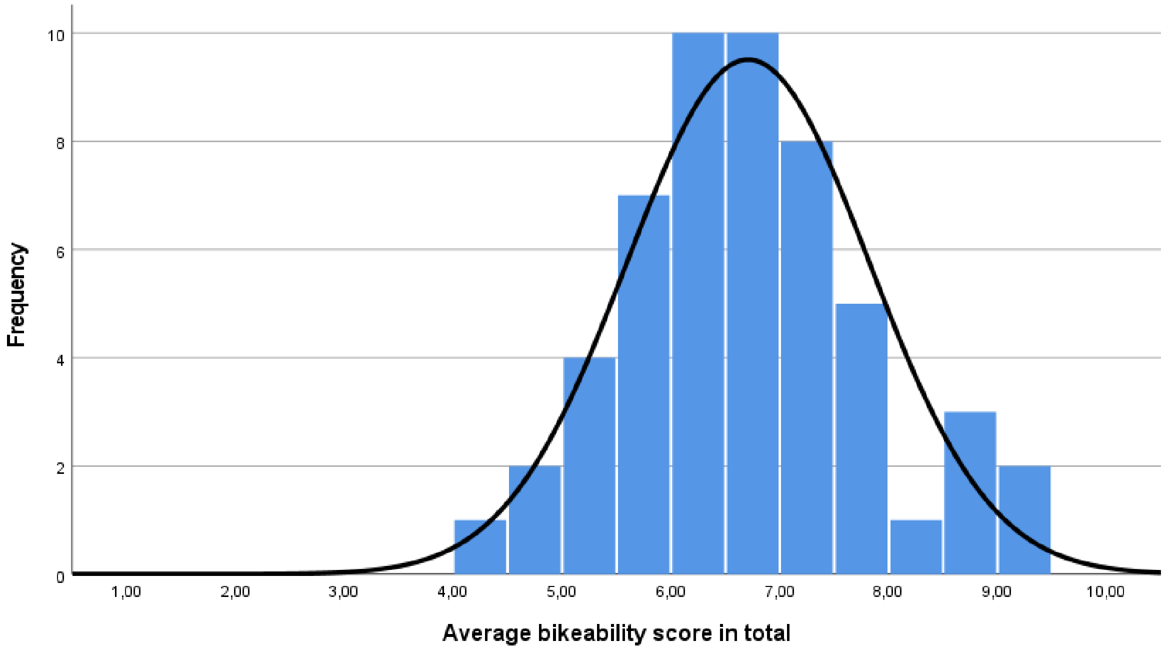

Figure 5.22: Division of the average bikeability scores per respondent. Rescaled to match the bikeability index' scale.

Average bikeability scores were also calculated for the neighbourhoods and for the city, only using the accompanying questions variables per area. The destination accessibility was left out in this case, as it doesn't distinguish neighbourhood or city. Consequently, these scores can only be compared to one another. The resulting statistics of all three 'average' variables can be seen in Table 5.7. The mean score for the complete bikeability, as it is perceived by the respondents, is 6,71 on a scale ranging from 1 to 10. This mean is considerably higher compared to the mean scores (of the municipality and inner city) that resulted from the GIS-analysis. However, this is a skewed comparison as both analyses are founded on completely different types of data.

Statistic / Variable	Minimum	Maximum	Range	Mean	Median
Total bikeability average	4,29	9,29	5,0	6,71	6,79
City bikeability average*	4,17	9,17	5,0	6,16	5,83
Neighbourhood bikeability average*	2,5	10,0	7,5	6,37	6,67

Table 5.7: Statistics per average perceived bikeability.
**Excluding destination accessibility component*

Looking at the statistics of the average bikeability in the city and neighbourhoods, the neighbourhood average has a large range and a slightly higher mean and median. To find out if this difference is statistically significant, a paired-samples t-test was carried out. This test is equivalent to the Wilcoxon signed-ranks test, but assumes the variable to be normally distributed, which is the case. However, the results of this test didn't indicate a significant difference and so it can be assumed that the research population doesn't have a different perception of bikeability in their neighbourhood than in the whole city of Nijmegen, based on adding up the separate indicators. Just like the separate components, the average scores were checked for possible relations with respondents' characteristics. This was done by conducting linear regression, to find ongoing, linear relations. On top of that, the three variables were grouped based on gender, neighbourhood, age class and general income group. The means of these groups were compared using an independent samples t-test (for gender and neighbourhood) and a one-way ANOVA test (for age class and income group). This resulted in one significant linear relation, namely general income group predicting the average bikeability score for the city, thus not taking into account destination accessibility. The output is shown in Table 5.8. It appears that higher incomes lead to lower perceptions of bikeability. This is partly due to the same linear relationship income has with the perception of the quality of the road network.

Variable	B	Beta	t	p
Constant	7,115		14,200	0,000
General Income group	-0,494	-0,273	-2,027	0,048*

Note. R^2adjusted = 0,056

Table 5.8: Regression analysis summary for independent variable 'general income group' predicting average bikeability score for the city, excluding destination accessibility.

5.2.3 Ranking of bikeability indicators

The second part of the survey includes the questions that have addressed the importance of the four aforementioned indicators. Respondents were first asked, per indicator, to what extent they valued this indicator as important for cycling. After all other questions were answered, they were asked to rank the indicators by order of importance, by dragging each of the indicators to 1st, 2nd, 3rd or 4th place. Looking at the SPSS output, this ranking resulted in four different variables that are interdependent, as respondents could only pick every option once. The frequency data of the ranking is visualized in the chart in Figure 5.23. There's a clear division between the rankings of distance to destinations and quality of cycling facilities on the one hand and connectivity and elevation difference on the other hand. More than half of the respondents valued distance to destinations as most important aspect for good bikeability. Another 40 percent thought safe and suitable cycling facilities are most important. On the other side of the chart the other two aspects are clearly found to be less important, as respectively 50 percent and 40 percent of the respondents put elevation difference and connectivity in last place.

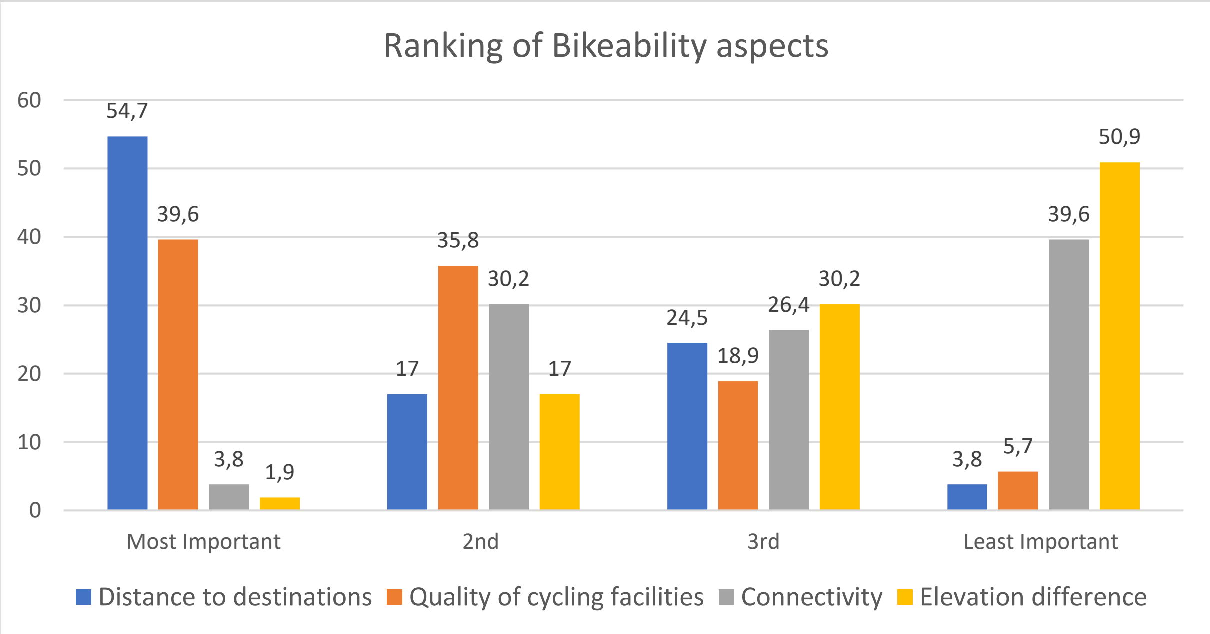

Figure 5.23: Comparison of ranking of bikeability aspects/components by respondents. Results are in percentages of total N = 53 respondents.

To check if and which rankings differ, a Friedman test with additional post-hoc analysis was conducted. As expected, a statistically significant difference between the ranking of the four different bikeability aspects was found, $X^2(3) = 57{,}023$, $p = 0{,}000$. To discover which rankings differ, a Post Hoc analysis was carried out, using Wilcoxon signed-rank tests combined with an applied Bonferroni correction, which set the significance level to $p = 0{,}008$ (0,05/6). Medians of the ranking of distance, quality of facilities, connectivity and elevation difference are 1, 2, 3 and 4, respectively. These tests indicated significant differences between rankings of: elevation difference and distance ($Z = -5{,}847$, $p = 0{,}000$), connectivity and distance ($Z = -4{,}448$, $p = 0{,}000$), elevation difference and quality of facilities ($Z = -4{,}950$, $p = 0{,}000$), and connectivity and quality of facilities ($Z = -4{,}959$, $p = 0{,}000$). However, no significant differences were found between rankings of quality of facilities and distance ($Z = -0{,}341$, $p = 0{,}733$) and connectivity and elevation difference ($Z = -1{,}409$, $p = 0{,}159$).

In conclusion, there is undisputable difference in ranking between the two most important aspects and the two least important aspects. However, the small difference between elevation difference and connectivity is not significant. The same holds for the ranking of distance to destinations and quality of cycling facilities. With this information, new weights can be applied to the different aspects, impacting the eventual bikeability.

In addition to differences between the four ranking variables, it is possible that different population groups within the sample rank one or more aspects differently. To check if this is the case, the medians of the ranks per group need to be compared and analysed by using two different tests. First, to find out if gender and neighbourhood of residence influence one or more ranking variables, the Mann-Whitney test was performed. The test results indicated that women (mean rank of 22,96) find distance to destinations more important than men do (mean rank of 30,89), $Z = -2,067$, $p = 0,042$. The other three rankings didn't have a difference for gender ($p > 0,20$). Regarding neighbourhood, the test results didn't indicate any significant difference for any of the four aspects ($p > 0,20$). Moving on to age class and (general) income group, a Kruskal Wallis test with optional post hoc analysis was carried out to find if these variables influence ranking of aspects. The test results indicated that both age class ($p > 0,20$ for all four aspects) and (general) income group ($p > 0,10$ for all four aspects) do not matter when the bikeability aspects are to be ranked.

Destination accessibility

The destination accessibility component, represented by distance to destinations in the survey, is composed of seven categories in the survey and GIS-analysis, unlike the other components. This makes it possible to assign different weights to the destination categories, if there are statistically significant differences between the destination variables. The respondents were asked to indicate how long they are willing to cycle to every type of destination. Seven options, in minutes, were given: less than 5, 5, 10, 15, 20, 30 and more than 30. In order to discover if there's significant difference between any of the seven destinations, a Friedman test was conducted. The frequencies of ranks and mean rank of the variables are shown in the chart in Figure 5.24.

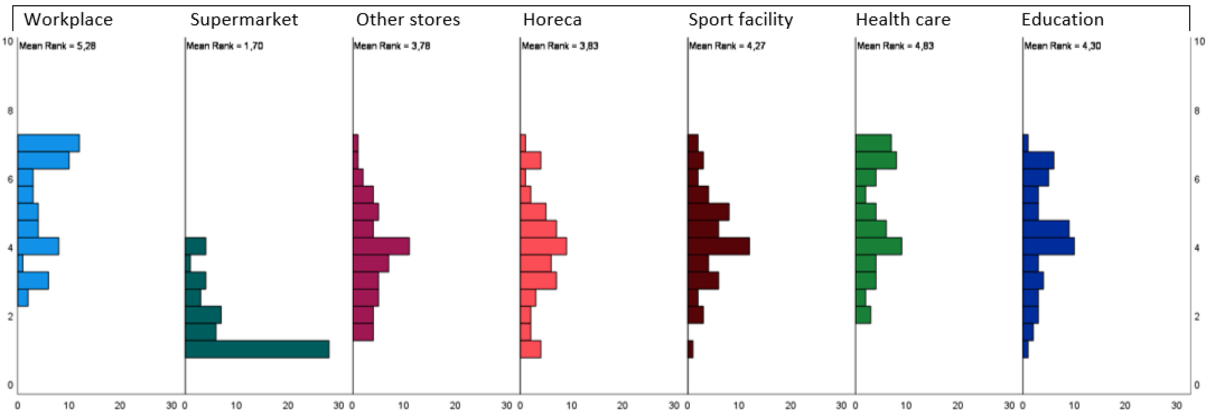

Figure 5.24: Frequencies of ranks of destination category variables. Y-axis shows rank (higher rank is longer time), X-axis shows number of respondents.

As expected, the test indicated that there is significant difference between the willingness to cycle to different destinations, $X^2(6) = 117,314$, $p = 0,000$. A post hoc analysis in the form of Wilcoxon signed-rank tests for every pair of variables was then conducted, taking into account the Bonferroni correction. The test results indicated that respondents aren't willing to cycle to the supermarket very far, as this variable clearly differs from all others, as $p = 0,000$ for all pairs. Furthermore, respondents are willing to cycle to work further than to other stores ($p = 0,007$)

and horeca (p = 0,011). Due to the large number of pairs, only the statistically significant differences are mentioned. In conclusion of this analysis, it appears that having a supermarket nearby is most important for bikeability and that the workplace doesn't have to be so close to maintain good bikeability. Therefore, the GIS destination category 'office' is applied a lower weight than the rest, while the category stores and shops (which includes supermarkets) is applied a slightly higher weight. The other destinations are kept the same.

5.2.4 Additional factors to bikeability

The closed-ended questions about perception and ranking of bikeability aspects in the survey have already been discussed and analysed. In addition to these questions, one open-ended question was posed at the end of the questionnaire, so qualitative data could be obtained. Respondents were asked to name and elaborate on any other factors or aspects of the physical environment that they deemed important as well as improvable for good bikeability in the city. A total of 24 respondents answered this question, with diverse outcomes. The answers can more or less be divided into four categories: social safety, traffic safety, cycling facilities and travel speed.

Regarding social safety, several respondents mentioned street lighting and even CCTV surveillance occurred in the data. When moving on to traffic safety, which was the category with the most input, respondents mentioned factors like separation from other traffic, safety of crossings, managing different types of cycling lane vehicles, and available space for cyclists at junctions and crossings. Besides general factors, several respondents mentioned specific roads or junctions that could be improved. Among these were the Muntweg and the crossing of the Thijmstraat with the Sint Annastraat (both Nije Veld). The third category concerns cycling facilities, which mostly consists of responses about bike parking facilities upon reaching a destination. The fourth category covers everything that is travel time or speed related. Respondents mentioned waiting time at traffic lights, complexity of junctions, number of obstacles along the route and traffic flow in general.

Based on this qualitative data, it seems that not many bikeability indicators can be directly derived from the responses, that are both new and suitable for GIS-analysis. However, there's one factor that has influence on both traffic safety and travel speed, namely crossings and junctions. Many of the negative factors that were mentioned by respondents are applicable on most larger junctions, such as long waiting times at traffic lights, not enough space for cyclists to wait and cross, unsafety of crossings and bad traffic flow. Hence, most larger junctions have a negative impact on the bikeability of an area or route. Therefore, this factor is included as a new indicator in the revised bikeability index, which is elaborated in subchapter 5.3.

5.3 Comparison

The results in the first two sub-chapters are based on different data sources, which has led to two different types of data analysis. In these analyses, the comparison between the case study neighbourhoods and the municipality of Nijmegen has been the main subject. In this third sub-chapter, the outcomes of the survey are applied on the remainder of the GIS-analysis, in which the bikeability index is adapted and improved.

5.3.1 Comparing perceptions to factual data

Directly comparing bikeability scores from the GIS-analysis to the rescaled, average Likert scale values is not useful and can lead to wrong assumptions. However, it can be interesting to see if the respondents 'disagree' with the outcome of the GIS-analysis. For example, the GIS-analysis points out that (one of) the neighbourhoods scores better for a certain indicator than the city does, while the respondents perceived the exact opposite for this indicator.

Firstly, both neighbourhoods come out on top in the GIS-analysis when it comes to the weighted mean density (0,62 and 0,59) of the road network, compared to the rest of the city (0,46). The survey results, however, indicated that the neighbourhood road network is not as suitable for cycling. This seems contradictory, but density and suitability are two different factors. The GIS raster further explains the outcome of the survey, as there are only a few roads coded with values 7 or 10, meaning that separated cycling lanes are scarce in these neighbourhoods.

To continue, connectivity scores in the GIS analysis are much higher for Wolfskuil and Nije Veld than for the whole municipality. The survey output shows a similar trend, because the question applying to the neighbourhoods was answered significantly more positive; respondents found their neighbourhoods to be better connected than the city in its entirety. The next analysed indicator is destination density. The average density score in the GIS analysis is high for the neighbourhoods compared to the municipality. This is in line with the answers of the respondents, as a vast majority could reach every destination by bike (within the time they were willing to cycle). The fourth component, elevation difference, doesn't have more impact on the bikeability of Wolfskuil than it has on the city's bikeability, according to the SPSS analysis. When this is compared to the mean slopes and mean scores of Wolfskuil and the municipality, there aren't any striking differences. The mean elevation difference score of Wolfskuil is only slightly lower than the one of the municipality.

Finally, the overall bikeability scores that were calculated in the GIS-analysis are higher for both neighbourhoods (6,01 and 6,27) than they are for the municipality or inner city (5,13 and 5,64). This isn't consistent with the output of the SPSS analysis. Though the calculated neighbourhood average is slightly higher (6,37) than that of the whole city (6,16), the difference was not found to be statistically significant.

5.3.2 Addition of relevant junctions to index

The qualitative data that was gathered and analysed in the survey has shown that there is another potential indicator that has an impact on the bikeability in Nijmegen. A substantial number of respondents mentioned annoyances, safety issues and obstacles that primarily exist around large junctions, intersections and crossings. The original bikeability index by Winters et al. (2013) uses the number of intersections as an indicator to measure bikeability. In the index, more intersections contribute to better bikeability, because many intersections give you the option to take many turns and choose shorter or faster routes by doing so. Initially, the choice was made to leave this indicator out of the research, because the advantage or disadvantage is unclear for the Dutch urban context. With the input from the survey, one can state that large junctions and intersections have an adverse effect on bikeability. Crossing one often involves waiting for traffic lights or for cars to pass, congestion on cycling lanes and sometimes even dangerous situations.

Therefore, the GIS-analysis is complemented with a new layer that contains points representing every large junction in Nijmegen. A large junction can be defined as a main road intersecting (intersection) or meeting (T-junction) with another main road, or with an important cycling route. Another condition has to be met, as not every large junction is necessarily bad for bikeability. A roundabout, for instance, improves bikeability rather than decreasing it. Therefore, only junctions with traffic lights were selected for the point layer. The junctions were picked one by one, using Google Streetview for reference. The resulting point layer was converted into a heat map and is displayed in Figure 5.25.

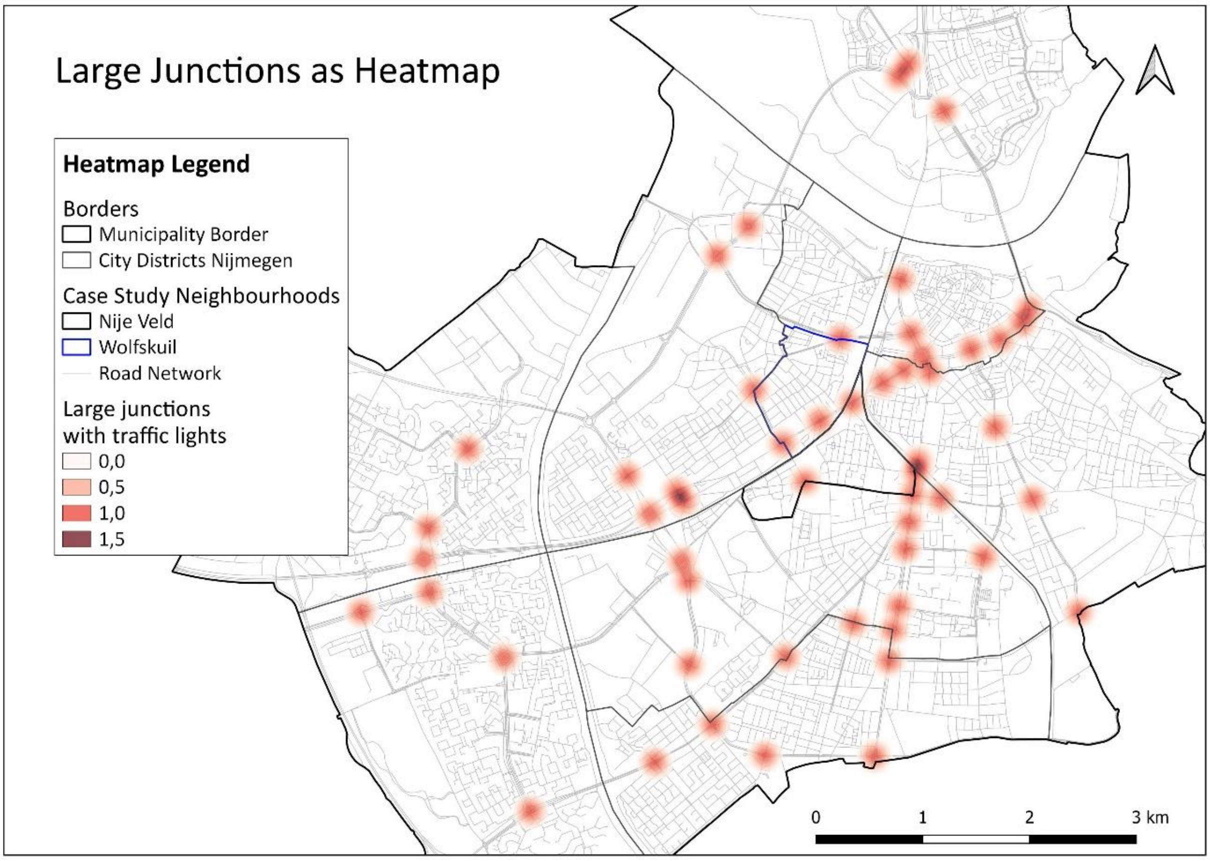

Figure 5.25: Every large junction in the municipality detrimental to bikeability. Measurement in legend is density, with values higher than 1 representing two junctions within the 170 metre radius.

On the map, each large junction appears as a red spot that impacts the surrounding area. The impact is limited to a 170 metre radius, which is enough to fully cover the largest junctions. Unlike the other indicators, this layer isn't directly part of the weighted bikeability that results from the formula. Instead, the heat map raster, which represents the density values, is subtracted from the resulting average bikeability raster. The density values are 1 in the middle of junctions and slowly decrease to 0 towards the edge of the 170 metre radius. This approach is chosen because the raster data is limited to the relatively small areas around junctions. Making it part of the average score would violate the reliability of the index. The heatmap shows that most junctions are located in the inner city, as Dukenburg, Lindenholt and Nijmegen Noord only have a few junctions that harm the bikeability. Most junctions can be found along two main roads: the Sint-Annastraat (10) and the Graafseweg (9). Both start in the centre at the Keizer Karelplein and lead south and southwest respectively. The fact that these roads traverse many other important streets and cycling route explains the large number of junctions with traffic lights.

5.3.2 Revised bikeability index of Nijmegen

The revised bikeability index is established by applying four changes to the index that was presented in the theoretical framework. These four changes, that are derived from the survey results, have been discussed in the previous paragraphs for the most part. However, one adjustment hasn't been covered yet. This adjustment that has been applied to the index concerns the scale and naming of the destinations indicator. The answers of the respondents regarding destination accessibility turned out to be very positive, with six out of seven destinations being accessible by bike for nearly every respondent. In response to these findings, the label of the indicator has been changed from destination density to destination accessibility, as this better embodies the input from the survey but also fits with the raster made in QGIS. In addition, the scale of the final raster has been changed; adding 0,5 point to the minimum of 1 (on the normal 1 to 10 scale) per destination category that is reachable by bike from any point within the municipality. This has been done to avoid the inappropriately low values in most of the municipality area for this indicator.

To measure this new minimum value, isochrones around points in every corner of the municipality were calculated in QGIS. The isochrones were divided in areas of 10, 15 and 20 minutes of cycling from the point in question. By laying every destination point layer on the isochrones layer separately, the corner points were checked for accessibility to destinations. This analysis showed that every type of destination can be reached by bike (based on the willingness to cycle in the survey) from any place within the municipality of Nijmegen. Therefore, the minimum of the indicators' scale has been changed to 4,5. Secondly, the destinations within the destination accessibility indicator have been applied different weights, as explained in paragraph 5.2.3. The category 'offices' has been applied a weight of 2, 'stores and shops' a weight of 5, while the rest of the categories have been applied a standard weight of 4. The visual result of the new heatmap only differs slightly from the original.

The third change concerns the new weights that have been applied to each indicator. The ranking in the survey showed that there's a clear difference between the two most important indicators (destination density and quality of cycling facilities) and the two least important indicators (connectivity and elevation difference). Therefore, the first two have been applied a weight of 2 and the least important indicators a weight of 1. The fourth and last change has been discussed in the previous paragraph and involves subtracting the density of the disadvantageous junctions from the average bikeability score.

Nijmegen

The result of the revised bikeability index for Nijmegen is depicted in Figure 5.26. The colour scheme is exactly similar to the bikeability output in Nijmegen with the original index, back in Figure 5.12, to make a visual comparison possible. Additionally, the actual difference per raster cell has been calculated by subtracting the first bikeability raster from the revised raster. The consequent raster, that makes use of 50 metre cells, can be seen in Figure 5.27.

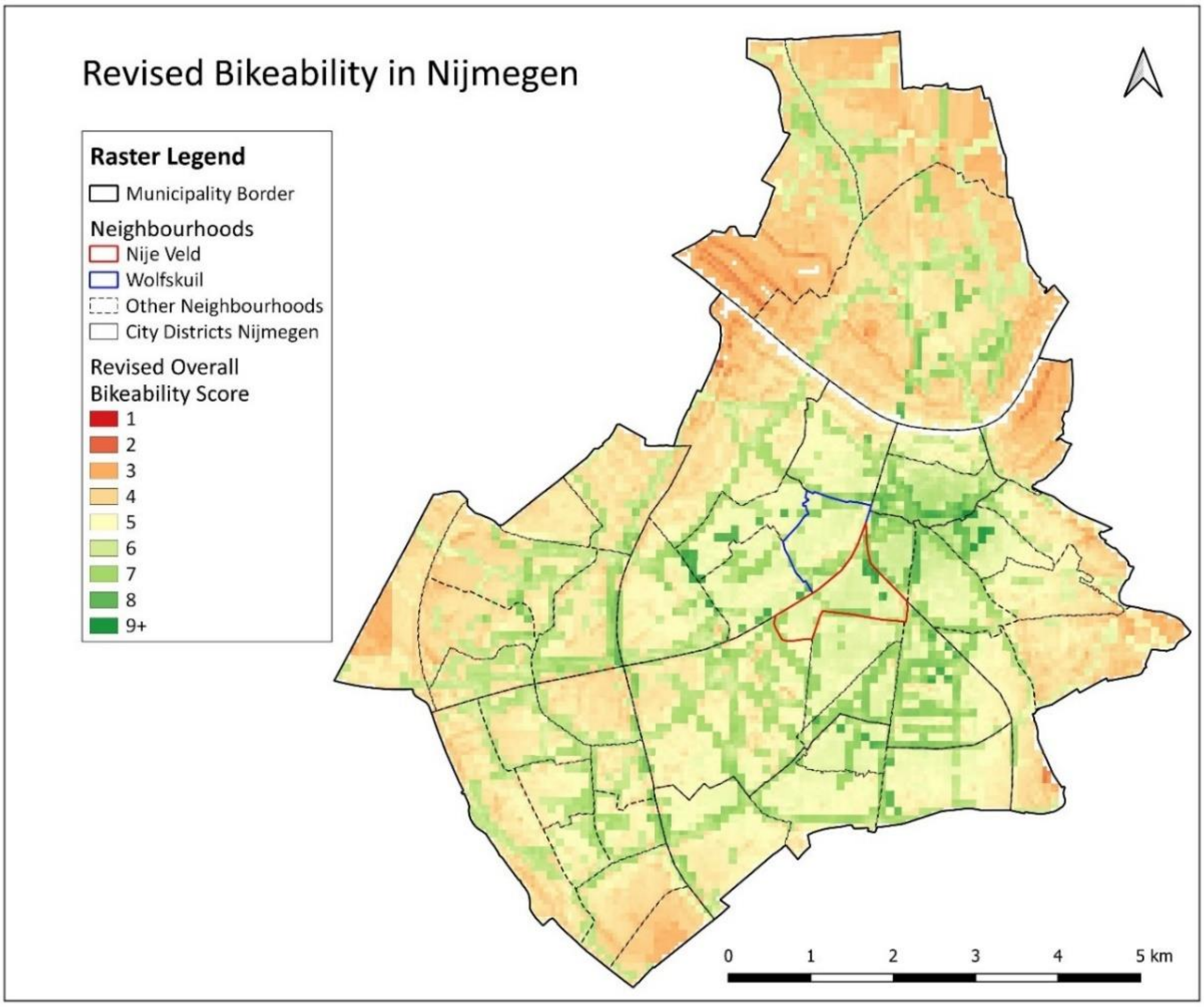

Figure 5.26: Overall bikeability scores in the municipality of Nijmegen, in accordance with the revised index.

Some obvious differences can be observed by looking at both rasters. The most striking change after revising the index is that bikeability is more balanced across the whole municipality; most red areas in Figure 5.27 can be found in the city centre and the surrounding neighbourhoods, including Nije Veld and Wolfskuil. This can be attributed to the addition of the complicated intersections, which appear as bright red spots on the map. However, the shifted balance in the city is predominantly caused by the rescalement of the destination accessibility indicator and its increased importance. Together with the higher weight of quality of cycling infrastructure, the city districts of Dukenburg, Lindenholt and Nijmegen Noord gain the most in this revised index.

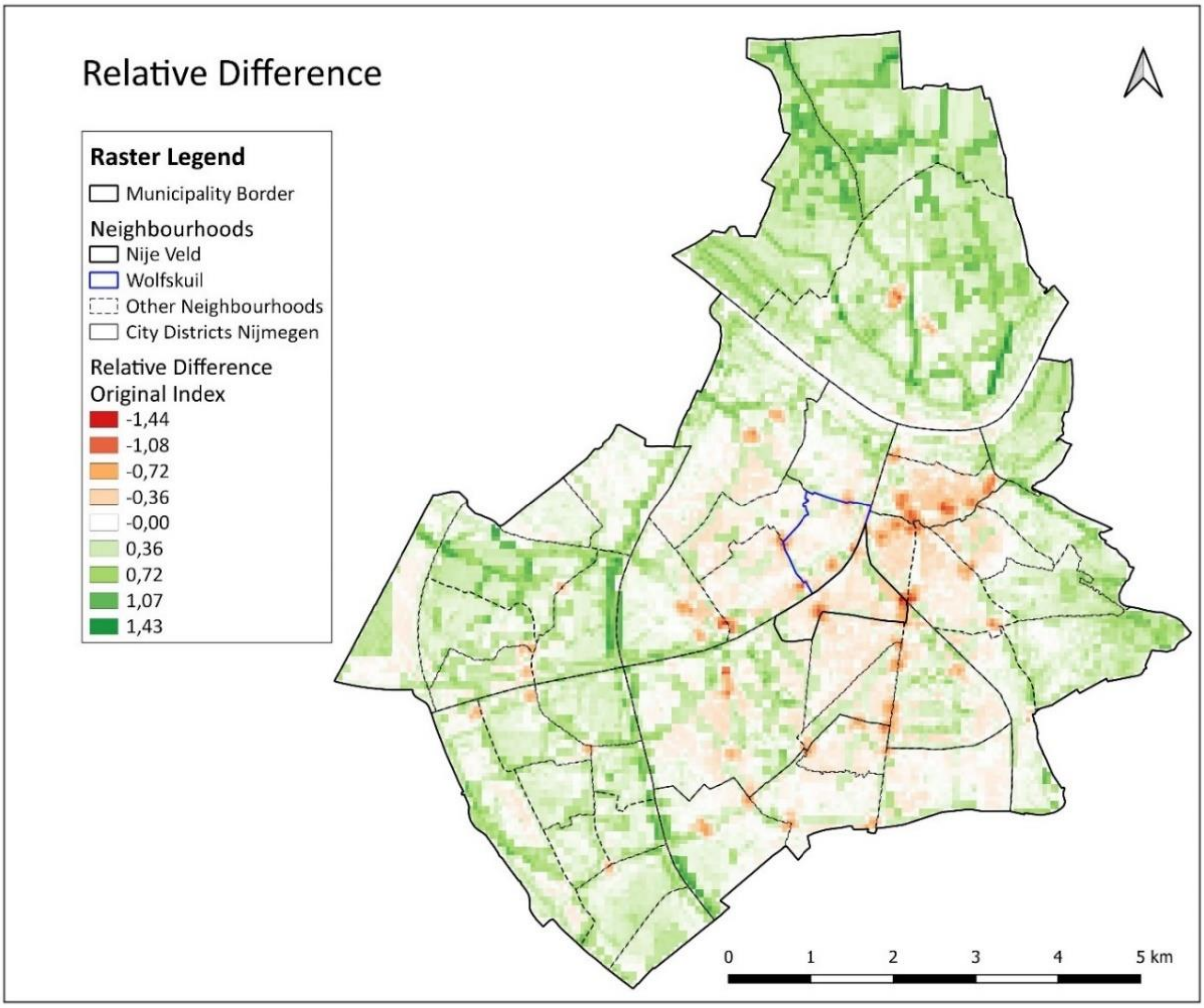

Figure 5.27: Relative difference between the original and revised bikeability. Red areas have lower scores in the revised index, while green areas represent higher scores.

In Figure 5.28 the relative difference for the cycable roads is displayed. It is needless to say that the discussed shift is reflected on the roads as well. The junctions that decrease bikeability are easy to spot, concentrating around the access roads originating from the centre. The statistics for all relevant areas are given in Table 5.9. The statistics from the original index are in brackets for comparison. Minimum and maximum scores are higher in general, just as the mean and median scores are slightly higher for the municipality and inner city. The improved balance of bikeability is expressed by the significantly lower range. The mutual differences between the municipality and the inner city are a little bit smaller, looking at the mean and median scores.

Statistics / **Area**	Minimum	Maximum	Range	Mean	Standard Deviation	Median
Nijmegen	**2,41** (1,35)	**9,35** (9,19)	**6,94** (7,84)	5,34 (5,13)	1,10 (1,13)	5,12 (5,04)
Inner City	2,41	9,35	6,94	5,72 (5,64)	1,04 (1,07)	5,50 (5,54)
Wolfskuil	4,74 (4,46)	7,88 (7,78)	3,15 (3,32)	5,96 (6,01)	**0,74** (0,73)	5,64 (5,77)
Nije Veld	4,37 (4,95)	8,84 (8,49)	4,47 (3,54)	**6,14** (6,27)	0,89 (0,76)	**5,83** (6,04)

Table 5.9: Overall score statistics per area for the revised bikeability index. Original index scores are in brackets.

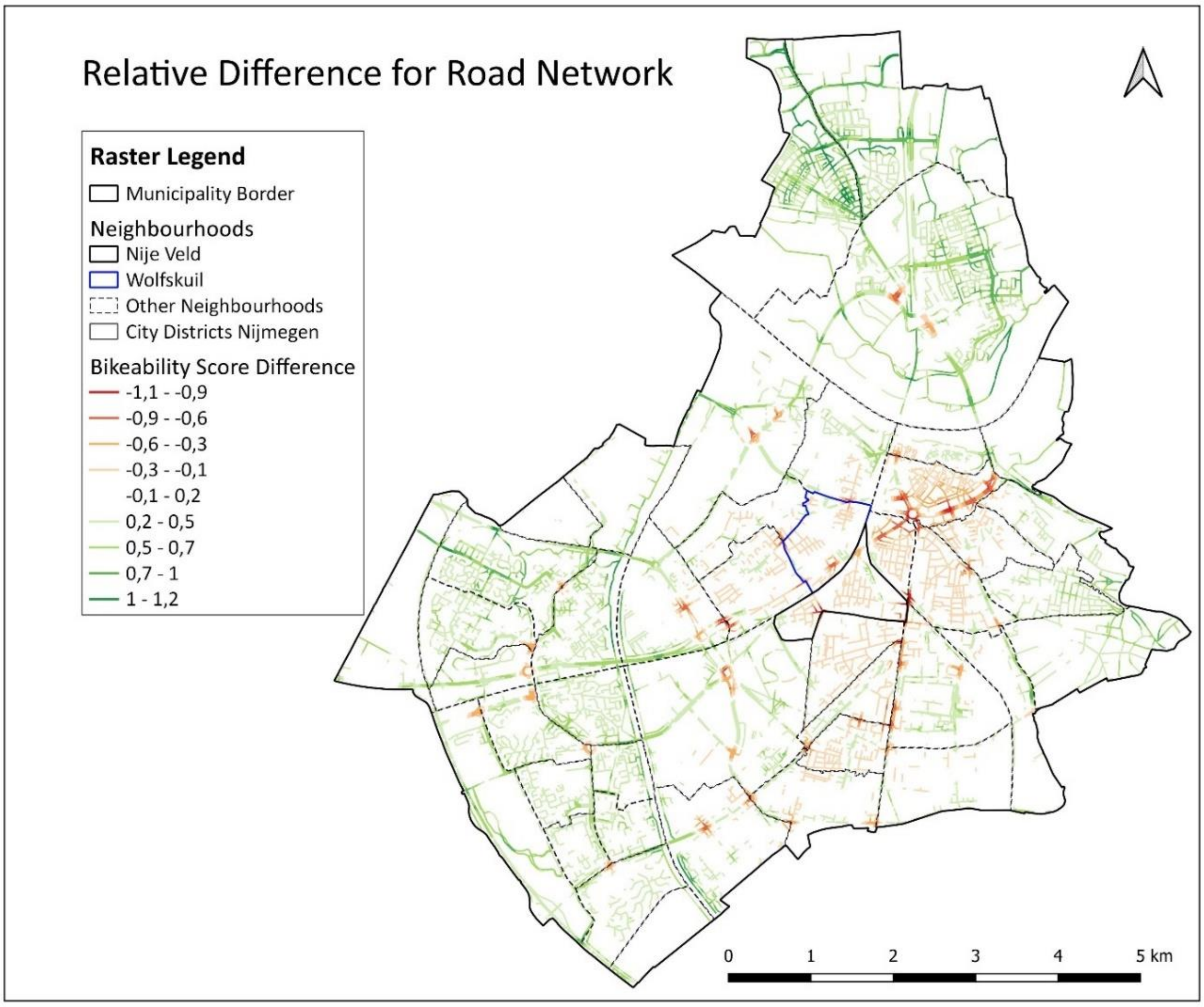

Figure 5.28: Relative difference of bikeability scores for the road network.

Wolfskuil and Nije Veld

The revised bikeability for the case study neighbourhoods has been calculated using the more detailed versions (with 5 metre cells) of the rasters for each indicator, as is the case for the original index. The map with the resulting raster can be seen in Figure 5.29, and the relative difference in Wolfskuil and Nije Veld between the original and updated index is displayed in Figure 5.30. Again, the same colour scheme has been applied for good comparison. In the neighbourhoods too, the scores are more balanced, as is the case for the whole city. The elevation difference in Wolfskuil is less prominently visible, as this indicator only counts half in this index, compared to destination accessibility and infrastructure quality. However, the dominant colour in Figure 5.29 is orange, while in the original index green was more present. This is mainly due to the doubled weight of the two most important indicators. Even though the minimum destination accessibility value was raised to 4,5, both neighbourhoods didn't profit from this as they already boasted relatively high scores. The same holds for the majority of the road network, that was valued with a score of 2 (no form of separated cycling lane), that has now been magnified.

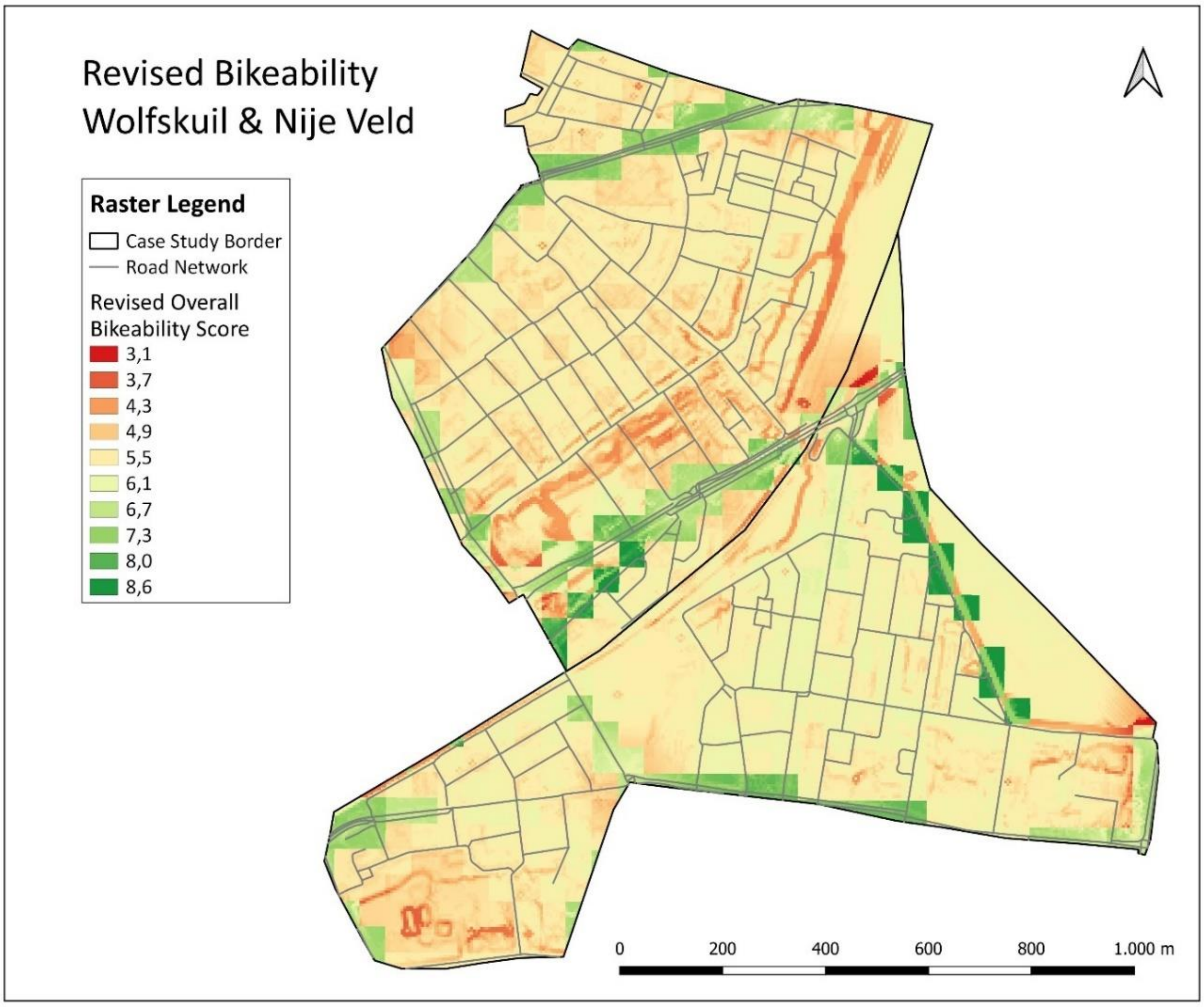

Figure 5.29: Overall bikeability scores in Wolfskuil and Nije Veld, in accordance with the revised index.

Looking at the statistics in Table 5.9, it seems that the revision of the index has had a different effect on the neighbourhoods than on the municipality. Also between both neighbourhoods, scores have changed differently. While the minimum score rose significantly in the municipality and in Wolfskuil, it declined in Nije Veld. On the other hand, the maximum score increased slightly for every area. This results in Wolfskuil having a lower range than before, while Nije Veld has a significantly higher range, which contrasts the increased balance in general. The mean and median scores in Nijmegen are higher in the revised index, which cannot be said for both neighbourhoods that have slightly decreased mean and median bikeability scores.

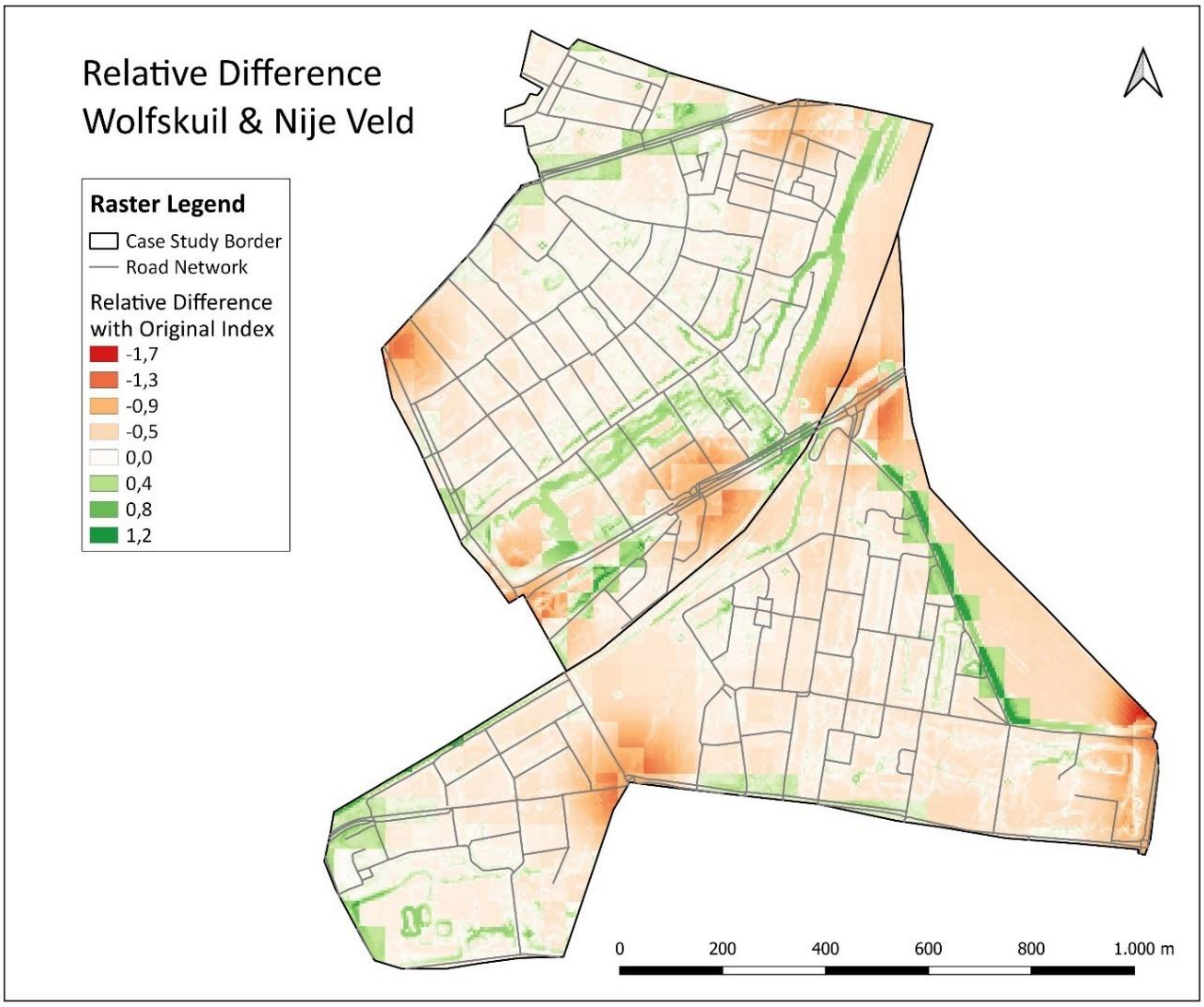

Figure 5.30: Relative difference between the original and revised bikeability in both neighbourhoods. Red areas have lower scores in the revised index, while green areas represent higher scores.

6. Conclusion

In this chapter the conclusions are presented by answering the sub-questions and subsequently answering the main research question. The conclusions are derived from the results of the GIS analyses and survey analysis, as well as the theoretical framework. The first sub-question to be answered is:

How bikeable are the neighbourhoods in the case study compared to the city as a whole, according to a bikeability index using objective indicators?

The first question covers the objectively measured bikeability that was calculated by using the 'standard' bikeability index. This index is a slightly adapted version of the index developed by Winters, Brauer, Setton and Teschke (2013), better suitable for the Dutch context. Four indicators within the physical environment (destination density, quality of infrastructure for cycling, elevation difference and connectivity) were used in the Geographical Information System (GIS) analysis, which was carried out in QGIS. For each indicator a separate analysis was carried out, which was followed by calculating the overall bikeability with the rasters of the indicators. In essence, the purpose of this first analysis was to acquire a null hypothesis that was completely based on objective data, creating a raw visualization of the bikeability. Therefore, all four indicators were applied the same weight, resulting in the following formula in QGIS, that makes use of the full rasters for each indicator:

(destination accessibility + cycling facilities + connectivity + elevation difference) / 4 = bikeability

From this first analysis, it can be concluded that both case study neighbourhoods in question (Wolfskuil and Nije Veld) have significantly better bikeability than the municipality and the inner city have on average. In a ranking including all 44 neighbourhoods in Nijmegen, Nije Veld and Wolfskuil are among the best bikeable (7th and 11th). This can mainly be attributed to the location of these neighbourhoods, as both are near the city centre and in the geographic middle of the municipality, which makes them score high on destination accessibility and density, as well as connectivity. The bikeability in the rest of the municipality follows the same tendency; high bikeability scores occur in and around the centre (higher than 6 on a 1-10 scale) and decreasing scores occur towards the low-rated neighbourhoods on the outskirts (lower than 5). Accordingly, the best bikeable areas can be found in the city centre and in the three neighbourhoods directly south of it (Bottendaal, Galgenveld and Altrade). Concluding the first sub-question, the objective bikeability has shown that there is a contradiction regarding the difference in scores between the older, central neighbourhoods in the inner city and the (relatively) new, suburban neighbourhoods on the edges of the municipality. The suburbs have more suitable cycling infrastructure than the older parts of the city and they lack any significant elevation differences, which would make these areas better cyclable than the inner city. However, what the inner city area lacks in infrastructure quality and flat terrain, it makes up for in destination density and connectivity. Thus following the objective bikeability, it can be said that good infrastructure for cyclists makes bikeability better in itself, but if there are few destinations to cycle to the infrastructure's impact is only marginal. After all, the vast majority of cycling trips are made for the purpose of transport rather than recreation.

How do inhabitants rate the bikeability in Nijmegen compared to their own neighbourhood, and which elements of the physical environment are of importance to them?

The GIS analysis was followed by a survey among the inhabitants of Wolfskuil and Nije Veld, which was focused on two research elements in particular: finding out the respondents' perceptions of the bikeability indicators in question and the amount of importance they attach to each of these indicators. Regarding the first element, there's no clear difference in bikeability perceptions between the city as a whole and the neighbourhoods. However, it can be said that the neighbourhood scores better in terms of connectivity, as respondents mostly agreed that they can reach other parts of the city quickly. The whole city scores better on quality of infrastructure. Several unsafe situations and roads in and around the neighbourhoods, mentioned by the inhabitants, could've had an impact on this outcome. As for elevation difference, there's no difference in perception between the two areas, so the short, steep slope in Wolfskuil doesn't impact bikeability that much in the end. Regarding destination accessibility, no difference was made between neighbourhoods and city. Instead, seven destination categories were distinguished. Except for the workplace, every destination located in the city is reachable by bike for almost all respondents.

Furthermore, statistical tests were conducted to find differences of perceptions between population groups. In general, different population groups do not rate bikeability (indicators) differently, one exception aside. Being in a higher income group leads to a lower regard of the quality of cycling infrastructure and leads to a lower perceived bikeability score. This conclusion should be drawn with caution though, as the income group of the respondents has been derived from 6-digit postal code data and thus is an average of all household incomes in this area. Unfortunately, the literature on the influence of income on cycling is inconclusive, which makes it hard to confirm this result (Heinen et al., 2010).

The second element of the survey involved ranking the indicators according to importance for cycling. The analysis of this ranking revealed an evident division: destination accessibility and the quality of cycling facilities are clearly found to have more influence on cycling than connectivity and elevation difference. The significance of the two most important factors is reflected in the literature. Especially infrastructure has a pivotal role for cycling in an international context, as good cycling facilities are often linked to overall safety and continuity of routes (Pikora, 2003). However, this aspect is less important in the Dutch context, where good cycling facilities are the norm rather than an exception (Engbers & Hendriksen, 2010). Therefore, Dutch citizens tend to prioritize other aspects to cycling. This could explain that destination accessibility/density is in turn found to be more important than infrastructure in the survey, even though this difference is not statistically significant. The importance of (mixed) land use, and thus destination density, is universally of influence on cycling behaviour (Ton et al., 2019). Women found this indicator even more important than men did, but for there's no evidence in literature to back this up. The perceived insignificance of elevation difference could have several reasons. Cycling up a steep hill is often perceived as unpleasant (unless it's for exercise), but cycling down is perceived as pleasant, which can balance the negative side (Heinen et al., 2010; Muñoz et al., 2016). Additionally, people who experience difficulty with cycling up hills often have an e-bike nowadays. The low ranking of connectivity could be due to the fact that it is a somewhat abstract concept. Even though the concept was explained clearly in the questionnaire, it seemed less significant to the respondents than distance to destinations and quality of infrastructure, that both are straightforward aspects. Connectivity is mentioned less in the literature as well.

An additional open-ended question allowed the respondents to express their own thoughts about other (physical) factors that matter to cycling. A significant number of responses could be linked to the negative effects of complicated and dangerous intersections and other junctions. Several examples of these in and around the case study neighbourhoods were named, which indicates that this is a real issue for cyclists. Apart from the given examples, several other, similar junctions could be identified within the municipality. This indicated that it is not only an issue within Wolfskuil and Nije Veld, but throughout the whole city.

To what extent do the results of the survey relate to the results of the first sub-question and how can these be combined to determine the actual bikeability?

There are some significant differences between the results of the GIS analysis and the SPSS analysis. Regarding the SPSS analysis, this concerns the respondents' perceptions of bikeability components in their city and neighbourhood. Looking at the overall bikeability scores resulting from both types of analyses, there's a clear difference. In QGIS, the bikeability was calculated to be considerably higher on average in Wolfskuil and Nije Veld than in the municipality. However, the SPSS analysis showed no statistically significant difference in perceived bikeability between the neighbourhoods and the whole city. The accumulated participants' perceptions of the neighbourhoods ranges from 2,5 to 10, which is considerably more than for the city in particular or both combined (4,17 – 9,17 and 4,29 – 9,29 respectively). Compared with the results from the objective analysis, it is the other way around. Here, the ranges of the neighbourhoods are more than twice as small as those from the municipality and inner city. This remarkable difference between two types of analyses proves that people may perceive things very differently than factual data initially indicates. This conclusion emphasizes the relevance of this study, as just an objective bikeability index might not be representative for a real-life situation.

The ranking that the respondents assigned to the indicators can be compared to the ranking/importance of the factors of the original bikeability index by Winters et al. (2013) (displayed in Figure 2.4). This results in some interesting differences, as well as similarities. While the participants clearly find destination accessibility and cycling infrastructure the most important, connectivity and elevation difference are found to be inferior. In the original index, bicycle facilities clearly come out on top, but distance and land use are only the 6th and 7th most important factors for cycling. Instead, traffic is the 2nd most important, while street network (part of connectivity) and topography (elevation difference) are 3th and 4th, which corresponds to this study's ranking. This ranking was based on the responses of 23 (potential) cyclists in the Vancouver region. Considering this, only half of the ranking is in line with the findings of Winters et al. (2013).

On top of that, the participants pointed out the harmful effect of some junctions, which is contradictory to one of the indicators in the original index, namely the number of intersections. A higher number of intersections would improve the connectivity. While the survey didn't necessarily point out that a higher intersection density is bad for bikeability, it did show that larger intersections with traffic lights slow progress and create dangerous situations. And as a higher intersection density correlates with higher urban density and heavy traffic, it is related to large and busy intersections. The convincing findings of the open-ended question were reason enough to add another indicator to the revised index. The revised index consists of five indicator indicators with the addition of all large junctions between two or more main roads with traffic lights.

Furthermore, the adaptation of the bikeability index relies on the changed weight of each indicator. The difference between the two most important and two less important aspects is reflected by the doubled weight of the destination accessibility and cycling infrastructure. The revised index also pays attention to the importance of each destination, that is reflected by adapted weights within this indicator. Besides this, the destination raster has been rescaled according to the inhabitants' perceptions. The bikeability index formula that has been used to calculate a more accurate bikeability image of Nijmegen was changed accordingly:

*(destination accessibility*2 + cycling facilities*2 + connectivity + elevation difference) / 6 - large junctions = bikeability*

The raster that came forth from calculating the revised index for Nijmegen, showed some interesting differences that are supported by the accompanying statistics of each area. Both case study neighbourhoods still have better bikeability scores than the inner city and the whole municipality, but the difference is significantly smaller than it was in the first analysis. Even more, the mean and median scores of both neighbourhoods have decreased a little. Among all 44 neighbourhoods in the municipality, Wolfskuil now ranks 10th, while Nije Veld ranks 8th. Concerning the other neighbourhoods, some of the best bikeable have lower means than before, while most other neighbourhoods have higher mean scores. Especially those in Dukenburg, Lindenholt and Nijmegen Noord have increased the most, which could be seen in Figure 5.27. Looking at the municipality as a whole, the revised index has provided a more balanced bikeability image of Nijmegen. However, some eye-catching, local differences with the original index can be seen. These have been brought about by adding the junction indicator. As a result, the bikeability score can be very high on a cycling street, but can drop a few points one hundred metres further upon reaching a crowded junction without proper cycling facilities. This is actually representative of the cycling experience in a city, which doesn't always change gradually, but is suddenly influenced by physical circumstances along the route.

The research process of this thesis, that starts with raw factual data and finally results in an accurate index that accounts for the perceptions of the inhabitants of Nijmegen, has been covered by answering the three sub-questions. Following this, the main research question can be answered:

How do the inhabitants of two neighbourhoods in Nijmegen perceive the bikeability in their city and how can this information be applied on a standard bikeability index, creating a more accurate, revised index in the process?

The inspiration and foundation for conducting this research stems from the existing bikeability index designed by Winter et al. in 2013. The index is the only one of its kind so far, in a sense that it uses geospatial data to measure how suitable an urban region is for cycling. Even though the index was designed in a different urban context, it has proven to be an objective and useful tool to systematically measure bikeability levels in the city of Nijmegen. The resulting rasters in QGIS showed high bikeability levels in and around the central neighbourhoods, but scores gradually decrease towards the municipality border. Along the main access roads leading into the city, bikeability is found to be better than in neighbouring areas. The original index forms a solid quantitative basis, but lacks in nuance and contextual elements. Conducting a survey among inhabitants of the case study neighbourhood provided the research with qualitative input. The respondents had different perceptions of what is important for cycling, compared to the original index.

Altogether, the survey analysis has proven that it was necessary to revise the original bikeability index in order to make it accurate and more suitable for the city of Nijmegen. Additionally, the data from the survey was essential in the process of doing this. The division of the ranking is the foundation of this improved index. The addition of major junctions as a fifth component came forth from the qualitative input of the survey. Finally, applying new weights to destinations and rescaling destination accessibility to be more accurate for the city of Nijmegen was decided upon the positive perception of this aspect. With these four adjustments put into effect, a more accurate rendering of the bikeability in Nijmegen was calculated. Applying the new index on the city has had a significant influence on the outcomes of this research. The most notable change is the shifted balance: on average the city has better bikeability, but the bikeability scores have increased the most west of the canal and north of the Waal. The junctions that have been added to the index clearly have their effect on bikeability of major roads, like the Sint Annastraat and Graafseweg. In other research within the Dutch context, it is reported that respondents often think nothing can be improved in terms of infrastructure, in contrary to this study. Many examples of problems and possible improvements, related to infrastructure, were given by the respondents. As opposed to the municipality, the bikeability scores for Wolfskuil and Nije Veld slightly decreased according to the revised index. This is in line with the opinion of the respondents about their neighbourhoods' bikeability, that is still lacking on some points.

7. Discussion

This chapter reflects on the findings and methodology of this study. Besides this, it discusses the limitations and makes recommendations for further research. In addition, recommendations for policy and practice in Nijmegen are made.

7.1 Reflection on the research results

Within the survey sample, four population characteristics were distinguished: gender, age, neighbourhood and income group. Analysing the survey data showed that only income group has significant influence on perceptions of (one indicator of) bikeability. However, in existing literature several other relations between those four characteristics and cycling behaviour have been defined. Less is known about perceptions for that matter, but perceptions are a strong determinant for cycling behaviour. Therefore, similar relations for perceptions could be expected. The reason for not finding any of these relations could be the small sample size, that consisted of even smaller population sub-groups, and that might have been too small for SPSS to notice a significant difference. With a larger survey sample or a sample focused on a specific group of the population, elderly people or people with low income for example, different perceptions and importance of indicators could be found. The same holds for a survey in a different type of neighbourhood. People living in the suburbs of Dukenburg or Lindenholt probably have a different perception of the four main bikeability indicators. According to the bikeability map, these districts have a lower level of destination accessibility and connectivity, but have better cycling infrastructure and lack any significant elevation difference. This would probably be reflected to some extent by the perceptions of the inhabitants. Lastly, ethnicity was not included in the survey, but could play an important role due to different levels of affinity with cycling among population groups with a migration background.

The qualitative data derived from the open question eventually led to adding a fifth aspect to the index. Whereas several of the respondents' answers were associated with the negative effects of large intersections, turning this into an extra indicator still required the data to be operationalised. This was done by identifying junctions across the whole municipality including the elements that respondents described as being adverse and unfriendly to bikeability. For this purpose, Google Streetview was used to inspect junctions for these elements, that include the presence of traffic lights and the intersection of two main roads or an important cycling route with a main road. Personal cycling experience in Nijmegen came in handy during this process, as I'm familiar with several junctions that slow down cycling progress and are potentially dangerous. Besides this, my own experience made it easier to relate to the perceptions of the inhabitants. Because of this, I could more easily value the problems that inhabitants encounter in the physical environment. On the other hand, already being familiar with a research subject, the physical environment in this case, can cloud the objective judgement of the researcher. This could eventually have consequences for the internal validity of the research.

The negative impact of junctions on cycling in Nijmegen is contradictory to the positive impact of a higher density of junctions in the original index, which has been mentioned briefly in the conclusion. The reason for this is probably embedded in the urban structure. Nijmegen has grown organically though different periods of time, which is reflected by an infrastructure that follows no clear pattern or system throughout the whole city. Vancouver on the other hand, where the index was designed, follows a clear grid pattern. Just like in most North-American cities, the road network consists predominantly of straight roads running from east to west and from north to south. In such a grid network, a higher density of intersections implies more equally fast routes for cyclists, who can more easily avoid congested routes and busy intersections. This is beneficial for the bikeability. In Nijmegen and many other European cities, one of the downsides of the more organic infrastructure is that busy, large junctions often can't be avoided. A higher density of intersections would in this case also mean more traffic-heavy junctions that are adverse to bikeability. Of course, small junctions with good cycling facilities and without traffic lights are good for bikeability, of which roundabouts can be an example.

7.2 Reflection on data collection

This study relies for the most part on secondary data. Most of the data was obtained from the PDOK website, a platform that makes high-end geospatial data available to the public. Just a fraction of the available data on PDOK was eventually used, as the website offers big data for the whole of the Netherlands. The use of big data is essential for geospatial sciences, but also comes with certain risks. The greater the quantity of data, the more statistically significant correlations appear. However, the number of correlations that actually represents a true causal relation doesn't increase accordingly. This can result in false correlations and false assumptions eventually (Fan et al., 2014). Therefore, the data from the survey among inhabitants also served as control data, that was used to triangulate the results of the GIS-analysis.

Another issue with the secondary data that needs to be addressed is the suitability of the data for the research. The data from PDOK is used for a broad spectrum of applications and not just for the purpose of measuring bikeability. Because of this, not all data was a perfect fit for the index. This can also be seen in the resulting maps of the indicators and the final bikeability. First of all, the slope was measured by using AHN data. These data give a very detailed and close-knit picture of the exact elevation above Normaal Amsterdams Peil (NAP). The AHN comes in rasters with different cell-sizes and the largest that was available for download was the raster with 5 metre cells. Therefore, every little detail of elevation and the resulting slopes is visible, including dyke slopes, slopes of bridge ramps and other manmade elevation differences. Of course, cycling doesn't take place on the actual slopes of a dyke or bridge ramp, but these elements are clearly visible as sharp edges on the bikeability map. A raster with much larger cells would solve this issue to some extent, as would an AHN that only shows natural elevation difference. The perfect solution would be an elevation profile for the entire road network, so only areas accessible by bike are influenced.

Secondly, the destination category is based on the BAG, that appoints one or more function of categories to a building. Of course, these categories also include housing, which cannot really be considered a destination. Another category is lodging, which includes hotels, campsites and vacation apartments. While it is possible to cycle to these destinations, they aren't considered day-to-day destinations for inhabitants of the same city. The BAG also doesn't distinguish between supermarkets or grocery stores and stores that don't sell food. This difference is significant for cycling though, as having a supermarket nearby is found to be more important than having a clothing store nearby. The connectivity and cycling infrastructure indicators are based on data from the NWB, the national road database. At first, the NWB for Nijmegen was from suitable for analysis of cycling infrastructure. Concerning road usage, it only distinguishes between main road users: bus lanes are used by buses, special cycling streets by cyclists and highways by cars. Any other road is labelled as 'mixed traffic'. Data about cycling lanes alongside roads is not available (for the city of Nijmegen). Due to this, most cycling lanes had to be identified manually, using OSM and Google Streetview. With an eye on increasing cycling for transport, information about cycling lane types could be included as attributes in the NWB. While most indicators could be analysed in QGIS only, measuring the connectivity required the use of space syntax, a scientific tool to analyse spatial layouts. This technique is an interesting scientific approach to accessibility and connectedness of public space. It can be of added value to mobility planning.

7.3 Limitations and recommendations for future research

As with most research, there are some limitations to this study as well. First of all, the results of the research may be hard to generalize for other cities as a whole, because the municipality of Nijmegen has a very specific urban context if all its social and physical characteristics are to be combined, just like any large Dutch city. As it has been mentioned in the conclusion, bikeability is, to a certain extent, dependent on the context and environment of a region or city. Within the Netherlands and some other Western European countries, the revised bikeability index can still be useful for cities of similar size. The research findings on neighbourhood level do have a better generalizability. Wolfskuil and Nije Veld can both be classified as pre-war, working-class neighbourhoods, located just outside the city centre. Many cities in the Netherlands have neighbourhoods of a similar type. The good and bad aspects, and the eventual bikeability scores of comparable neighbourhoods could therefore be surprisingly similar. All in all, the external validity is dependent on the scale of the results, but this is also one of the consequences of a case study. Nonetheless, the methodology used to arrive at a new index is very much generalizable and can be used in further research to analyse bikeability in other places.

Secondly, an index to measure bikeability still is a niche, as the index provided by Winters et al. (2013) is the only of its sort. Therefore, the theoretical foundation of this study relies on this index, that was developed in the urban context of Vancouver. This might've harmed the reliability of the research, even though the index was first adapted to the Dutch context. The lack of previous research on bikeability, especially about the Netherlands, made it difficult to apply changes to the index that were also substantiated by existing theories. Due to this, the final results rely heavily on the input from the survey. Here lies an opportunity for future research. To measure bikeability even more accurately, a new index designed from scratch would be the most reliable. This requires more in-depth research into cycling culture, infrastructure, land use and maybe even more factors that influence cycling. The PASTA framework designed by Götschi et al. (2017) could serve as a good starting point for a more comprehensive index. An index designed especially for the Netherlands, with Dutch values in mind, can provide insight into cycling bottlenecks and other existing issues. This kind of information would have the power to improve the current policy for cycling.

Besides this, the questionnaire was conducted within a period of six days at the beginning of October. The beginning of autumn could've had an effect on the perception of cycling in general, as the spring and summer months are often more inviting for cycling. On top of that, the weather varied during these six days, which could've had influence on the consistency of people's perception of cycling. Further research could be done into the effects of weather and seasons on people's perception of cycling. Another limitation to the survey part of the research is the sample size, which was relatively small looking at the population of both neighbourhoods. A larger sample would improve the confidence level and margin of error of the results and ultimately the reliability of the survey. In order to acquire many more respondents, the data would have to be collected in a less time-consuming way than going from door-to-door. Delivering flyers with a QR-code and providing an incentive could be an option then.

Furthermore, the case study in this thesis was limited to two somewhat similar neighbourhoods. On the one hand, it was interesting to see if there were any unexpected (big) differences between the two. On the other hand, it would've been more interesting and scientifically justified if two very different neighbourhoods were chosen. Given the difference in bikeability scores, new research could compare neighbourhoods around the city centre with neighbourhoods in the suburbs. The way the data is analysed in GIS is very suitable for making more detailed and extensive comparisons. Additionally, it could be interesting to analyse the bikeability for a larger area than just one city. The cell-size of the raster that has been used now would work even better for larger areas, for example the whole urban region of Arnhem-Nijmegen.

7.4 Recommendations for policy and practice

The results and conclusion of this thesis can be of use to developers of policy and other people with an interest in the field of transport planning. Hence, some recommendations for the cycling practice in Nijmegen are given first. Then a general recommendation for implementation of a bikeability index is given.

Improving complicated junctions for cyclists

The results of the survey showed that a number of junctions in Nijmegen is harmful for the city's overall good bikeability. Like many European cities, Nijmegen has a historical city centre, around which new city districts have been built during different periods in time. This has made the city quite organic, but it has also created complicated traffic related issues. Several important intersections are historically not suited to process large amounts of traffic. Cars, cyclists and pedestrians sometimes have to wait disproportionally long for the lights to turn green. This slows down progress, increases travel time and at some junctions this can create dangerous situations. There is much to be gained by redesigning the most inefficient junctions and making them more favourable for cyclists. As a result, progress by bicycle will become faster in comparison with progress by car. This could decrease the number of cars and increase the number of cyclists on the road.

Introducing more separated cycling lanes

Separated cycling lanes have several advantages over non-separated cycling lanes and normal roads. Not only do they provide more safety, cycling on separated lanes is more comfortable and makes for quicker progress. The same goes for special cycling streets. All in all, these infrastructural changes make cycling more attractive. Nijmegen-Noord, Dukenburg and Lindenholt already have a lot of separated lanes and routes exclusively for cyclists, but progress could be made in the inner city. Especially Nijmegen Oost and the case study neighbourhoods have few separated cycling lanes.

Reducing the impact of major barriers on cycling

There are several natural and manmade barriers in Nijmegen that have an impact on bikeability. The most significant barriers are the Waal and the Maas-Waalkanaal, which act as borders between the inner city and the suburbs despite the multiple bridges. The train tracks coming from the south and southeast form significant barriers as well. The tracks' overpasses create even more slopes on top of those created by natural elevation differences. Although it isn't possible to erase these barriers for cyclists, their impact on cycling could be further reduced. This could be done by making the routes crossing these barriers as favourable as possible for cyclists. Regarding the larger bridges and their run-ups this has already been done, but the overpasses of the train tracks could be improved, as well as the area around the central station. The latter is going to be renovated in 2024.

Promoting cycling (in suburbs)

The main societal goal of this study is to increase the share of cycling in the urban mobility context. To achieve this goal, improvements of the physical environment are necessary. But these improvements are pointless for people that are not accustomed to cycling in any way. Therefore, it is essential to promote cycling among all layers of the population. Especially in those parts of the city that have lower bikeability scores and that are further away from the city centre. Relatively many people with a low SES live in these parts. Dukenburg, Lindenholt and Hatert all have some of the highest low-education and income assistance percentages. Besides this, a relatively large part of the population has a non-western migration background (Gemeente Nijmegen, 2021). This has consequences for the share of cycling in these neighbourhoods. Therefore, promoting cycling is what is most necessary here.

Giving people reason to cycle

This recommendation is related to the previous one. The results of the GIS-analysis showed that there is a trade-off between the suburbs and the city centre: The lack of different destinations within good proximity in some suburbs can't be made up for by the generally good cycling infrastructure. In the inner city this is more or less the other way around, as there is a good variety of destinations within close proximity, but a lesser cycling infrastructure in general. However, if there aren't any destinations to cycle to, the benefit of a perfect network of cycling routes to bikeability is minimal. One of those suburbs is Dukenburg, which has plenty of cycling lanes, but not many different types of destinations. Many offices and shops that sell large products, like furnishing stores, are located in Dukenburg. The city district is predominantly orientated on car traffic, which is not only reflected by its land use, but also by the wide roads that prioritize car traffic. Moreover, the distance to the city centre varies between six and eight kilometres, which is often found to be too far for most people to cycle. Lindenholt has the same issues, but is located a bit closer to the city centre. For these reasons cycling is a relatively unattractive mode of transport for the districts' inhabitants, even though the bikeability score isn't too bad. In order to make cycling more attractive here, destination accessibility should be improved. This requires a change in land use, which is hard to bring about. Another option is to develop a fast cycling route that runs through Dukenburg and/or Lindenholt, which connects Nijmegen with Wijchen and eventually Oss. This would improve connectivity and makes cycling through these parts more pleasant, just like the RijnWaalpad has done for Nijmegen-Noord. Together with the rising popularity of the e-bike, the remoteness of the suburbs would be less of an issue.

Giving cyclists the space they need

The last recommendation that can be derived from this study concerns the growing number of cycling lane users. The total use of cycling lanes might not have increased much in recent years, but the number of different types of users has. 'Normal' cyclists share the same spaces with people on regular e-bikes, speed pedelecs, scooters and racing bikes, with take-away and grocery couriers on e-bikes, and with package deliverers on cargo bikes. The bike being used in many diverse ways is a good development in general, but the cycling facilities need to accommodate this. Cycling lanes might have to be wider on some routes to allow for safe overtaking of speed pedelecs on normal bikes, for example. The speed and size differences in general ask for more space on cycling lanes and waiting sections at traffic lights.

Implementation of index in practice

The results and methods of this thesis can be of use to developers of policy and other people with an interest in the field of transport planning. Measuring bikeability with an index in QGIS or any other geographical information system functions as a good starting point to get a deeper understanding of cycling behaviour in a city or region. However, for the index to be of actual value to policy makers and spatial planners, the local context needs to be researched and applied. By doing this, visual differences in the bikeability map can be explained by the correct causal relationships, avoiding any wrong prejudices and assumptions. In order to make the GIS method and process suitable for planning practice, a special data package could be composed. This package should include all data needed to measure the bikeability indicators accurately, without the big data limitations this study had to deal with. The actual bikeability can differ per city or region, as the concept of bikeability is partly dependent on the local context. Therefore, municipalities and provinces that make use of the index must take into account the qualitative component as well. This implies finding out how the bikeability is perceived by inhabitants. This could be done by means of citizen participation. For example, to find out on what bikeability aspects a neighbourhood is lacking, planners could ask the neighbourhood council for input, who on their turn ask the inhabitants for input. An alternative could be an online survey among inhabitants. This is similar to the method in this study, but a municipality or province has a much higher potential reach of respondents, which makes a survey even more useful and reliable. Instead of targeting the whole population, the focus could also be shifted to a specific population group (elderly people, immigrants, etc.), in order to find out how bikeability could be improved for this group.

Finally, the use and approach of a geospatial index doesn't have to be limited to cycling only. The concept of walkability already is more common and equally, if not more important than bikeability, thus a similar index could work for the mode of walking as well. The use of a bikeability index makes sense, looking at the current spatial planning practice in the Netherlands. The new physical environment act (Omgevingswet) is to be implemented by governmental bodies this year. This act incorporates many current laws and rules involving the physical environment and aims to make policy and planning easier and more predictable, but it leaves space for contextual adaptation. Within this act, a standard bikeability index could function as a general guideline, with the qualitative, contextual input as the adaptation.

References

Bertram, D. (2007). Likert scales. *Retrieved November*, *2*(10).

Besussi, E., & Batty, M. (2010). *The Structure and Form of Urban Settlements Solstice: An Electronic Journal of Geography and Mathematics View project Agent-based Modeling and GIS View project*.

Centraal Bureau voor de Statistiek. (2022). Dashboard verkeer en vervoer. Derived from: https://www.cbs.nl/nl-nl/visualisaties/verkeer-en-vervoer

Centraal Bureau voor de Statistiek. (2020, April 28). Statline: Mobiliteitstrend; per rit, vervoerwijzen, reismotief, leeftijd en geslacht. Derived from: https://opendata.cbs.nl/#/CBS/nl/dataset/84755NED/table?dl=3D0FE

Cervero, R., & Kockelman, K. (1997). Travel demand and the 3Ds: Density, diversity, and design. *Transportation research part D: Transport and environment*, *2*(3), 199-219.

Christiansen, L. B., Cerin, E., Badland, H., Kerr, J., Davey, R., Troelsen, J., ... & Sallis, J. F. (2016). International comparisons of the associations between objective measures of the built environment and transport-related walking and cycling: IPEN adult study. *Journal of Transport & Health*, *3*(4), 467-478.

Creswell, J. W., & Poth, C. N. (2016). *Qualitative inquiry and research design: Choosing among five approaches*. Sage publications.

CROW. (2021). CO2-uitstoot verkeer. *Staat van de Mobiliteitstransitie.* Derived from: https://www.crow.nl/duurzame-mobiliteit/home/ruimte-voor-klimaat-en-energie/co2-uitstoot-verkeer-groeit#

De Haas, M., Hamersma, M. (2020). Fietsfeiten: nieuwe inzichten. *Kennisinstituut voor mobiliteitsbeleid.*

Engbers, L. H., & Hendriksen, I. J. (2010). Characteristics of a population of commuter cyclists in the Netherlands: perceived barriers and facilitators in the personal, social and physical environment. *International Journal of Behavioral Nutrition and Physical Activity*, *7*(1), 1-5.

Europese Commissie. (2020). Langetermijnstrategie voor 2050. *Climate Action.* Derived from: https://ec.europa.eu/clima/eu-action/climate-strategies-targets/2050-long-term-strategy_nl

Ewing, R., & Cervero, R. (2010). Travel and the built environment: A meta-analysis. *Journal of the American planning association*, *76*(3), 265-294.

Ewing, R., & Cervero, R. (2001). Travel and the built environment: a synthesis. *Transportation research record*, *1780*(1), 87-114.

Fan, J., Han, F., & Liu, H. (2014). Challenges of big data analysis. *National science review*, *1*(2), 293-314.

Field, A. (2013). Discovering statistics using IBM SPSS statistics. sage.

Fraser, S. D., & Lock, K. (2011). Cycling for transport and public health: a systematic review of the effect of the environment on cycling. *European journal of public health*, *21*(6), 738-743.

Gao, J., Kamphuis, C. B., Dijst, M., & Helbich, M. (2018). The role of the natural and built environment in cycling duration in the Netherlands. *International journal of behavioral nutrition and physical activity*, *15*(1), 1-16.

Gehl, J. (2013). *Cities for people*. Island press.

Gemeente Nijmegen. (2019). Nijmegen goed op weg. *Ambitiedocument mobiliteit 2019-2030.*

Gemeente Nijmegen. (2020, June). Nijmegen: Stad in beweging. *Omgevingsvisie 2020-2040.*

Gemeente Nijmegen. (2021). Cijfers over Nijmegen en haar bewoners. Derived from: https://public.tableau.com/app/profile/gemeentenijmegen

Goel, R., Goodman, A., Aldred, R., Nakamura, R., Tatah, L., Garcia, L. M. T., ... & Woodcock, J. (2021). Cycling behaviour in 17 countries across 6 continents: levels of cycling, who cycles, for what purpose, and how far?. *Transport Reviews*, 1-24.

Götschi, T., de Nazelle, A., Brand, C., Gerike, R., Alasya, B., Anaya, E., Avila-Palencia, I., Banister, D., Bartana, I., Benvenuti, F., Boschetti, F., Brand, C., Buekers, J., Carniel, L., Carrasco Turigas, G., Castro, A., Cianfano, M., Clark, A., Cole-Hunter, T., … Zeuschner, V. (2017). Towards a Comprehensive Conceptual Framework of Active Travel Behavior: a Review and Synthesis of Published Frameworks. *Current Environmental Health Reports*, *4*(3), 286–295.

Guba, E. G. (1990). The paradigm dialog. In *Alternative paradigms conference, mar, 1989, indiana u, school of education, san francisco, ca, us*. Sage Publications, Inc.

Guba, E. G., & Lincoln, Y. S. (1994). Competing paradigms in qualitative research. *Handbook of qualitative research*, *2*(163-194), 105.

Guetterman, T. C., & Fetters, M. D. (2018). Two Methodological Approaches to the Integration of Mixed Methods and Case Study Designs: A Systematic Review. *American Behavioral Scientist*.

Handy, S. L., Boarnet, M. G., Ewing, R., & Killingsworth, R. E. (2002). How the built environment affects physical activity: views from urban planning. *American journal of preventive medicine*, *23*(2), 64-73.

Handy, S., Van Wee, B., & Kroesen, M. (2014). Promoting cycling for transport: research needs and challenges. *Transport reviews*, *34*(1), 4-24.

Harkey, D. L., Reinfurt, D. W., & Knuiman, M. (1998). Development of the bicycle compatibility index. *Transportation research record*, *1636*(1), 13-20.

Harms, L., Bertolini, L., & Brömmelstroet, M. T. (2016). Performance of municipal cycling policies in medium-sized cities in the Netherlands since 2000. *Transport Reviews*, *36*(1), 134-162.

Hassler, U., & Kohler, N. (2014). Resilience in the built environment.

Heinen, E., Van Wee, B., & Maat, K. (2010). Commuting by bicycle: an overview of the literature. *Transport reviews*, *30*(1), 59-96.

Hillier, B. (2008, January 14). Using DepthMap for urban analysis: a simple guide on what to do once you have an analysable map in the system. *The Bartlett School of Graduate Studies.*

Kennisinstituut voor mobiliteitsbeleid. (2019). Mobiliteitsbeeld 2019. Derived from: https://www.kimnet.nl/mobiliteitsbeeld/mobiliteitsbeeld-2019#/

Kerr, J., Emond, J. A., Badland, H., Reis, R., Sarmiento, O., Carlson, J., ... & Natarajan, L. (2016). Perceived neighborhood environmental attributes associated with walking and cycling for transport among adult residents of 17 cities in 12 countries: the IPEN study. *Environmental health perspectives*, *124*(3), 290-298.

Koszowski, C., Gerike, R., Hubrich, S., Götschi, T., Pohle, M., & Wittwer, R. (2019). Active mobility: bringing together transport planning, urban planning, and public health. In *Towards User-Centric Transport in Europe* (pp. 149-171). Springer, Cham.

Lawrence, D. L., & Low, S. M. (1990). The built environment and spatial form. *Annual review of anthropology*, *19*(1), 453-505.

Ma, L., & Dill, J. (2017). Do people's perceptions of neighborhood bikeability match" reality"?. *Journal of transport and land use*, *10*(1), 291-308.

Ma, Liang, & Cao, J. (2019). How perceptions mediate the effects of the built environment on travel behavior? *Transportation*, *46*(1), 175–197.

Marquart, H., Schlink, U., & Ueberham, M. (2020). The planned and the perceived city: A comparison of cyclists' and decision-makers' views on cycling quality. *Journal of transport geography*, *82*, 102602.

Muñoz, B., Monzon, A., & Daziano, R. A. (2016). The increasing role of latent variables in modelling bicycle mode choice. *Transport Reviews*, *36*(6), 737-771.

Oja, P., Titze, S., Bauman, A., De Geus, B., Krenn, P., Reger-Nash, B., & Kohlberger, T. (2011). Health benefits of cycling: a systematic review. *J Med Sci Sports*, *21*(4), 496–509.

PDOK. (n.d.) Hét platform voor hoogwaardige geodata. Retrieved from: https://www.pdok.nl/

Pikora, T., Giles-Corti, B., Bull, F., Jamrozik, K., & Donovan, R. (2003). Developing a framework for assessment of the environmental determinants of walking and cycling. *Social Science and Medicine*, *56*(8), 1693–1703.

Philipsen, E. (2018). Een brug te ver? Een onderzoek naar de fietsbaarheid van Arnhem.

Pucher, J., & Buehler, R. (2008). Making cycling irresistible: lessons from the Netherlands, Denmark and Germany. *Transport reviews*, *28*(4), 495-528.

Rahi, S. (2017). Research design and methods: A systematic review of research paradigms, sampling issues and instruments development. *International Journal of Economics & Management Sciences*, *6*(2), 1-5.

Rijksoverheid. (2021, July). Nationale Broeikasgasemissies volgens IPCC. Derived from: http://www.emissieregistratie.nl/erpubliek/erpub/international/broeikasgassen.aspx

Sanchez, B. (2018). The space we use (when choosing transport mode). *Medium*

Space syntax network. (n.d.) space syntax. Derived from: https://www.spacesyntax.net/

Stichting wetenschappelijk onderzoek verkeersveiligheid (2020, November). Infrastructuur voor voetgangers en fietsers. SWOV-factsheet. Derived from: https://www.swov.nl/feiten-cijfers/factsheet/infrastructuur-voor-voetgangers-en-fietsers

Tan, W., Koster, H., & Hoogerbrugge, M. (2013). *Knooppuntontwikkeling in Nederland:(hoe) moeten we Transit-Oriented Development implementeren?*. Den HaagPlatform31.

Ton, D., Cats, O., Duives, D., & Hoogendoorn, S. (2017). How do people cycle in Amsterdam? Estimating cyclists' route choice determinants using GPS data from an urban area. In *The 96th annual meeting of the transportation research board: the* (pp. 1-12).

Ton, D., Duives, D. C., Cats, O., Hoogendoorn-Lanser, S., & Hoogendoorn, S. P. (2019). Cycling or walking? Determinants of mode choice in the Netherlands. *Transportation research part A: policy and practice*, *123*, 7-23.

University College London. (n.d.). depthmapX: visual and spatial network analysis software. Derived from: https://www.ucl.ac.uk/bartlett/architecture/research/space-syntax/depthmapx

Van Bergen, J. (2017, November 15). Dit zijn de langste straatnamen van Nijmegen. *Indebuurt.* Derived from: https://indebuurt.nl/nijmegen/nieuws/opmerkelijk/dit-zijn-de-langste-straatnamen-van-nijmegen~13236/7/

Van der Bijl, R. (2018, December 3). Wat is een fiets? Het fietssysteem in kaart gebracht. *Fietscommunity.* Derived from: https://www.fietscommunity.nl/blogs/wat-is-een-fiets-het-fietssysteem-in-kaart-gebracht/

Van Leeuwen, N., & Venema, J. (2021, March 5). Statistische gegevens per vierkant en postcode 2020-2019-2018. *Centraal Bureau voor de Statistiek.* Derived from: https://www.google.com/search?q=cbs+afkorting&oq=cbs+af&aqs=chrome.1.69i57j0i512l6j69i60.7467j0j7&sourceid=chrome&ie=UTF-8

Vereniging van Nederlandse Gemeenten. (2018). Omgevingsvisie. *Onderdeel van Omgevingswet.* Derived from: https://vng.nl/artikelen/omgevingsvisie

Walker, B., Holling, C. S., Carpenter, S. R., & Kinzig, A. (2004). Resilience, adaptability and transformability in social–ecological systems. *Ecology and society*, *9*(2).

Williams, C. (2007). Research methods. Journal of Business & Economics Research (JBER), 5(3).

Winters, M., Brauer, M., Setton, E. M., & Teschke, K. (2013). Mapping bikeability: a spatial tool to support sustainable travel. *Environment and Planning B: Planning and Design*, *40*(5), 865-883.

Yang, Y., Wu, X., Zhou, P., Gou, Z., & Lu, Y. (2019). Towards a cycling-friendly city: An updated review of the associations between built environment and cycling behaviors (2007–2017). *Journal of Transport & Health*, *14*, 100613.

Yin, R. K. (2011). *Applications of case study research*. sage.

Wang, Y., Chau, C. K., Ng, W. Y., & Leung, T. M. (2016). A review on the effects of physical built environment attributes on enhancing walking and cycling activity levels within residential neighborhoods. *Cities*, *50*, 1-15.

Willis, D. P., Manaugh, K., & El-Geneidy, A. (2015). Cycling under influence: summarizing the influence of perceptions, attitudes, habits, and social environments on cycling for transportation. *International Journal of Sustainable Transportation*, *9*(8), 565-579.

Appendix I: Explanation QGIS procedure

In this part of the appendix, a specific description of the procedure in QGIS that preceded the results in chapter 5 is given. QGIS is free, open source software that can be downloaded with several third-party plug-ins included. Within the software, all tools can be searched for in the processing toolbox.

Quality of cycling facilities

The analysis of the first indicator of the bikeability index concerned identifying the presence and separation level of cycling lanes.

1) First, the NWB geodata file is downloaded from the PDOK website. The layer can then be dragged onto the mapping canvas. For referencing it is convenient to use Open Street Map as base layer.
2) Only the roads in Nijmegen are of interest, so all roads outside the municipality border are cut out. The geoprocessing tool 'clip' is used for this purpose.
3) Because new data is to be created, a new attribute field is added in the attribute table menu of the layer, consisting of numerical values, called infra_intg.
4) There are four options for the level of separation. The highest level of separation is a cycling street. All road sections that are cycling streets are now selected, by editing the layer. The selection of cycling streets can be added to the new field 'infra_intg' and is appointed a value of 10.
5) The same is done for separated cycling lanes, but a value of 7 is appointed. All marked cycling lanes are appointed a value of 5 and the remaining roads a value of 2. To see which roads have which cycling lane type, Google Streetview and OSM are used.
6) Then the layer is converted to a raster. This is done with the conversion tool 'rasterise'. The raster fully covers the municipality and this is why all areas with no roads get a value of 1 in the raster. The raster cell size is set to 50 metres, so the roads turn out clearly visible.
7) The resulting raster comes out as a square covering the whole municipality, therefore the raster is clipped within the municipality border, using the 'clip' tool again.
8) The raster still needs a proper colour rendering. This is done by selecting a suitable colour ramp (white to green) in the symbology section of the properties menu.

Connectivity

For this indicator, the same NWB is used again, but it is initially analysed with the program depthmapXnet, which is downloadable for free.

1) Again, only the roads in Nijmegen are of interest, thus the 'clip' tool is used again in QGIS. The resulting layer is then saved as a .mif file (mapinfo file) to make it suitable for depthmap.

2) In depthmap, under 'file', a new project is created. Then the road database for Nijmegen is imported under 'map'. This opens up the option 'convert active map' that is used to convert the road network to a segment map.
3) Next up is the analysis of the network, which consists of segments (of lines). Therefore, under 'tools', an angular segment analysis is performed. This analysis calculates the shortest path between one point and another or series of other points. There are different ways to find the shortest path. Angular segment analysis does this by minimizing the accumulated angle between two points and determines the radius based on the number of junctions (or segments). Topological analysis calculates the shortest path based on the number of turns and metric analysis is founded on the physically shortest path.
4) In the analysis menu, the maximum number of tulip bins is selected (1024), the 'include choice' box is checked and for radius N is chosen, which means every path from every node to all other nodes is accounted for.
5) After completing the analysis, the created data map is saved as .mif again, so it includes all analysed measurements (integration, choice, depth and node count). The file can be loaded in the QGIS project now.
6) If the layer isn't georeferenced anymore due to the process, it has to be reprojected on the right coordinate system (CRS) using the tool 'warp' or 'reproject'.
7) The analysed measurements are now visible in the attribute table. With the properties menu the integration of the road network, which is the best measurement for connectivity, can now be visualized with the right colour ramp.
8) Thereupon, the vector layer is rasterised, again with a cell size of 50 metres. The raster doesn't cover the whole municipality yet, so the tool 'fill no data' is used to cover up most holes in the raster. The raster is then rescaled to match the 1-10 bikeability score scale. After that, the remaining blank spaces are appointed a value of 1.
9) Finally, the raster is clipped within the municipality border and given an appropriate colour scheme.

Destination accessibility/density

The analysis of this indicator is based on the density of each type of destination. For this purpose, the BAG is used. These geospatial data are more difficult to download from PDOK due to frequent changes and additions. In this case, the BAG is provided by the supervisor of this thesis.

1) The BAG is a point layer that contains a point for every building in the Netherlands. First, the layer is clipped within the municipality border. Each building has one or more of the eleven functions in total in the attribute table. Out of those eleven, seven functions have been used as destination categories.
2) For each function separately, a new point layer with all points with this function is made. This is done by using the 'split vector layer' tool.
3) When this is done for each relevant category, the new point layers are converted to a heatmap (eponymous tool), which is a raster type of layer. It calculates the density of a point layer based on the influence of each point (1000 metres) and the kernel shape (epanechnikov).
4) All seven heatmaps are then rescaled to a 1-10 scale ('rescale' tool) and subsequently rounded ('rounding' tool) to whole numbers.
5) To cover the whole municipality, the heatmaps are merged (using the tool 'merge') with a blank raster that has a score of 1 for the whole area, to make sure that every heatmap covers the entirety of Nijmegen.

6) In the raster calculator, the heatmaps are added up and the sum is divided by seven, by which a total 'average' heatmap is calculated.
7) Finally, the raster is clipped within the municipality border and given an appropriate colour scheme.

Elevation difference

The last indicator is analysed by using the AHN. These data come in rasters of different cell sizes and differ in measurement: AHN is not only measured from ground level, but also from the top of buildings. In this case, the AHN measured from ground level with a 5 metre cell size is used.

1) Because the AHN is a raster layer carrying much more information than a vector layer, it comes in many smaller rectangular maps instead of one large map. Seven small maps are downloaded to cover the entire municipality.
2) These maps are combined into one by using the 'merge' tool. Thereafter, the merged map is clipped within the municipality border.
3) The elevation map still has a lot of 'dead' pixels that are missing data. With the tool 'fill no data' these pixels are given an estimated value based on the surrounding pixels. This creates a smoother map.
4) To calculate the slope, a tool with the same name is used. This calculates the difference between every neighbouring pixel, resulting in the general slope.
5) To match the bikeability score scale, the raster is rescaled to a 1-10 scale, with a completely flat surface having a score of 10 and a surface with a slope of 18% or higher having a score of 1.
6) Finally, a suitable colour ramp is chosen that highlights the significant slopes the best.

Large junctions

The addition of this indicator to the index is a little different compared to the first four. The resulting raster only covers the areas around the relevant junctions. For this purpose, the NWB is used as a reference layer.

1) The junctions are selected with the aid of Google Streetview and the researchers' own experience. A new layer is created via 'create layer' and 'new shapefile layer' with the objects being points. No additional attributes are made, because only the location of the points matters.
2) Points are manually added to the new layer by clicking the rights spots on the map and giving them a number.
3) The point layer is then turned into a heatmap with a 170 metre impact radius for each point and the epanechnikov kernel shape.
4) The values of the heatmap range from 0 to 1,8 as the middle of each point has a density of 1 and the middle of two points within 170 metres has a density of up to 1,8. These values are already suitable for the eventual bikeability formula.
5) Because the indicator is deducted from the average score instead of being part of it, the indicator needs to have a minimum value higher than zero for the entire municipality. Therefore, the heatmap is merged with a blank raster again, that has a single value of a little more than zero.
6) Finally, the raster is clipped within the municipality border and given an appropriate colour scheme.

(Revised) Bikeability

The eventual bikeability maps are a combination of the discussed rasters per indicator:

1) First, the objective bikeability is calculated with the raster calculator using the following formula: (destination accessibility + cycling facilities + connectivity + elevation difference) / 4 = bikeability
2) The resulting raster is assigned a representative colour scheme, which is the red-yellow-green colour ramp in this case.
3) For the revised index, the formula that is used is: (destination accessibility*2 + cycling facilities*2 + connectivity + elevation difference) / 6 - large junctions = bikeability
4) The same red-yellow-green colour ramp is used for the revised map.
5) To make a profile of the bikeability for the road network, the tool 'cross profiles' is used on the layer with the road network.

In order to give every map a presentable look in this thesis, the option 'new printing layout' is chosen under the project tab. This opens a new window that allows for raw layers to be edited to a real map. In this window, a legend, scale bar, north arrow and title are given. Lastly, the result is exported as an image.

Appendix II: Questionnaire

The questionnaire was conducted with Qualtrics on a tablet. All respondents have completed the same questionnaire, which was in Dutch.

Beste meneer/mevrouw,

Voor mijn afstudeerscriptie doe ik onderzoek naar de fiets als vervoermiddel in Nijmegen. Ik focus me op de wijken Wolfskuil en Nije Veld (Willemskwartier) en daarom ben ik benieuwd naar uw mening over fietsen in deze wijk en in de stad.

Om dit te bepalen kijk ik naar vier verschillende eigenschappen van de ruimte: de veiligheid van wegen en fietspaden, de afstand tot bestemmingen, het hoogteverschil en de snelheid van een fietsroute (connectiviteit).

De vragenlijst bestaat uit twee gedeeltes. Het eerste gedeelte bestaat uit 14 meerkeuzevragen over de hierboven genoemde eigenschappen. Het tweede gedeelte betreft een tweetal open vragen. Deelname aan het onderzoek is anoniem. Het invullen van de enquête duurt ongeveer 5 tot 10 minuten.

Bij voorbaat hartelijk dank voor uw deelname!

Leeftijd:………………..
Geslacht:…………………
Postcode:………………..

Gesloten vragen

De eerste 3 vragen gaan over de afstand tot bestemmingen.

1. Hoe lang bent u bereid te fietsen (in minuten) om bij de volgende bestemmingen te komen?
Werk – *<5 / 5 / 10 / 15 / 20 / 30 / >30*
Supermarkt – *<5 / 5 / 10 / 15 / 20 / 30 / >30*
Andere winkels – *<5 / 5 / 10 / 15 / 20 / 30 / >30*
Horeca – *<5 / 5 / 10 / 15 / 20 / 30 / >30*
Sportfaciliteiten – *<5 / 5 / 10 / 15 / 20 / 30 / >30*

Gezondheidszorg – *<5 / 5 / 10 / 15 / 20 / 30 / >30*
Onderwijs – *<5 / 5 / 10 / 15 / 20 / 30 / >30*

2. Kunt u de volgende bestemmingen bereiken met de fiets binnen de tijd die u bereid bent te fietsen?
Werk – *ja/nee*
Supermarkt – *ja/nee*
Andere winkels – *ja/nee*
Horeca – *ja/nee*
Sportfaciliteiten – *ja/nee*
Gezondheidszorg – *ja/nee*
Onderwijs – *ja/nee*

3. In hoeverre vindt u het belangrijk dat er verschillende soorten bestemmingen dichtbij elkaar zijn? Denk bijvoorbeeld aan combinaties als winkels en horeca, sport en school, sport en werk, werk en school, etc.
Zeer belangrijk / belangrijk / redelijk belangrijk / enigszins belangrijk / onbelangrijk

De volgende 3 vragen gaan over de wegen en fietspaden.

4. In hoeverre vindt u het belangrijk dat het fietspad gescheiden is van de weg waar de auto's op rijden wanneer u fietst?
Zeer belangrijk / belangrijk / redelijk belangrijk / enigszins belangrijk / onbelangrijk
5. In hoeverre bent u het eens met de volgende stelling?
'De wegen in Nijmegen zijn geschikt en veilig voor fietsers.'
Helemaal eens / eens / neutraal / oneens / helemaal oneens
6. In hoeverre bent u het eens met de volgende stelling?
'De wegen in **deze wijk** zijn geschikt en veilig voor fietsers.'
Helemaal eens / eens / neutraal / oneens / helemaal oneens

De volgende 3 vragen gaan over het hoogteverschil.

7. In hoeverre vindt u het belangrijk dat de route die u fietst vlak is?
Zeer belangrijk / belangrijk / redelijk belangrijk / enigszins belangrijk / onbelangrijk
8. In welke mate heeft het hoogteverschil in Nijmegen volgens u invloed op hoe geschikt de stad is om in te fietsen?
Erg grote invloed / grote invloed / matige invloed / nauwelijks invloed / geen invloed
9. In welke mate heeft het hoogteverschil in Wolfskuil volgens u invloed op hoe geschikt de wijk is om in te fietsen?
Erg grote invloed / grote invloed / matige invloed / nauwelijks invloed / geen invloed

De laatste meerkeuzevragen gaan over de connectiviteit van fietsroutes. Dit kan bijvoorbeeld gaan over het aantal kruispunten dat overgestoken moet worden; of de route een rechte lijn is of juist zigzagt; of dat er andere te vermijden obstakels op de route liggen (treinspoor, snelweg, rivier/kanaal).

10. In hoeverre vindt u het belangrijk dat u met de fiets zo min mogelijk afslagen hoeft te nemen?
Zeer belangrijk / belangrijk / redelijk belangrijk / enigszins belangrijk / onbelangrijk
11. In hoeverre vindt u het belangrijk dat u met de fiets zo min mogelijk over hoeft te steken en op stoplichten moet wachten?
Zeer belangrijk / belangrijk / redelijk belangrijk / enigszins belangrijk / onbelangrijk

12. 'Alle stadsdelen en wijken in Nijmegen zijn onderling met elkaar verbonden door snelle en directe fietsroutes.'
Helemaal eens / eens / neutraal / oneens / helemaal oneens

13. In hoeverre bent u het eens met de volgende stelling?
'Ik heb het idee dat ik op de fiets vanuit huis snel in een ander deel van de stad kan zijn.'
Helemaal eens / eens / neutraal / oneens / helemaal oneens

14. Kunt u de 4 hierboven besproken eigenschappen rangschikken op volgorde van hoe belangrijk u ze vindt wanneer u fietst?

1. ………………………………………..
2. ………………………………………..
3. ………………………………………..
4. ………………………………………..

Open vragen

15. Zijn er, naast de besproken eigenschappen, andere ruimtelijke eigenschappen of factoren die u van belang vindt voor het fietsen in de stad? Als dit niet het geval is mag u het vak leeg laten.

……
……
……
……………………………

16. Op welke plek zou u deze factor(en) rangschikken in de volgorde bij vraag 14 (1 = belangrijkste factor; 5 = minst belangrijke factor)?
……
……
……
……………………………

Bedankt voor de tijd die u heeft genomen om aan deze enquête deel te nemen.

Uw antwoord is geregistreerd.

Appendix III: Full Bikeability statistics

Bikeability score statistics per city district, ranked by highest mean score:

Statistic / City District	Original Mean	Updated Mean	Original Minimum	Updated Minimum	Original Maximum	Updated Maximum
1. Nijmegen-Centrum	6,60	6,47	3,91	4,42	9,19	9,35
2. Nijmegen-Midden	5,95	6,00	3,24	3,78	8,49	8,84
3. Nijmegen-Oud-West	5,73	5,78	3,37	3,86	8,10	8,16
4. Nijmegen-Zuid	5,67	5,73	3,32	3,74	8,08	8,53
5. Nijmegen-Nieuw-West	5,34	5,45	1,35	2,41	8,32	8,68
6. Nijmegen-Oost	5,08	5,27	1,59	2,62	9,00	9,27
7. Dukenburg	5,00	5,27	2,83	3,39	7,31	8,01
8. Lindenholt	4,95	5,23	2,55	3,19	8,01	8,40
9. Nijmegen-Noord	4,32	4,75	1,63	2,59	7,84	8,31

Bikeability score statistics per neighbourhood, ranked by highest mean score. Numbers in red and green indicate a higher or lower ranking in the revised index:

Statistic / Neighbourhood	Original Mean	Updated Mean	Original Minimum	Updated Minimum	Original Maximum	Updated Maximum
1. Stadscentrum (City Centre)	7,10	6,86	4,45	5,23	9,19	9,35
2. Bottendaal	7,00	6,76	5,13	4,26	8,40	8,47
3. St. Anna	6,61	6,58	5,15	4,60	7,87	8,39
4. Galgenveld (5)	6,41	6,31	4,37	4,25	8,51	8,33
5. Altrade (6)	6,34	6,31	4,70	4,86	9,00	9,27
6. Hatertse Hei (7)	6,28	6,21	5,19	4,93	8,08	8,53
7. Nije Veld (8)	**6,27**	**6,14**	**4,95**	**4,37**	**8,49**	**8,84**
8. Heijendaal (4)	6,24	6,31	4,15	4,48	8,24	8,67
9. Hees (9)	6,07	6,11	4,96	4,96	8,30	8,67
10. Hazenkamp (11)	6,04	5,96	4,75	5,00	7,85	8,37
11. Wolfskuil (10)	**6,01**	**5,96**	**4,46**	**4,73**	**7,78**	**7,88**
12. Heseveld (12)	5,98	5,95	4,38	4,68	8,32	8,67
13. Grootstal (15)	5,78	5,80	4,30	4,41	7,51	7,63
14. Malvert (13)	5,63	5,95	3,75	4,09	7,05	7,83
15. Goffert (16)	5,60	5,73	3,24	3,78	7,35	7,80
16. Brakkenstein (24)	5,59	5,62	4,27	4,51	7,70	8,28
17. Neerbosch-Oost (18)	5,56	5,70	3,42	3,77	8,31	8,68
18. Biezen (22)	5,55	5,67	3,37	3,86	8,10	8,16
19. Benedenstad (20)	5,54	5,69	3,91	4,42	7,42	7,55
20. Kerkenbos (17)	5,51	5,72	3,70	3,94	7,06	7,05
21. Aldenhof (21)	5,44	5,68	4,01	4,43	7,06	7,32
22. Hatert (25)	5,42	5,59	3,32	3,74	7,43	7,93

23. De Kamp (14)	5,42	5,83	2,95	3,53	8,02	8,40
24. Meijhorst (23)	5,39	5,66	3,94	4,44	6,96	7,26
25. Lankforst (19)	5,35	5,70	3,71	4,24	7,31	8,01
26. Tolhuis (26)	5,32	5,56	3,73	4,02	6,93	7,15
27. Groenewoud (28)	5,10	5,25	1,59	2,62	7,45	7,60
28. Westkanaaldijk (31)	5,00	5,18	3,46	3,80	7,03	7,71
29. Staddijk (29)	4,95	5,19	2,83	3,57	6,66	7,04
30. ’t Acker (27)	4,94	5,36	2,62	3,43	6,82	7,61
31. Hengstdal (30)	4,91	5,19	3,18	3,85	6,67	7,07
32. Neerbosch-West (38)	4,81	4,91	3,86	4,13	6,65	6,99
33. ’t Broek (34)	4,80	5,09	2,79	3,33	7,04	7,77
34. Haven- en industrieterrein (36)	4,80	4,95	1,35	2,41	7,14	7,33
35. Zwanenveld (32)	4,79	5,14	3,20	3,84	6,98	7,60
36. Hunnerberg (33)	4,78	5,10	2,26	3,07	7,65	7,63
37. Weezenhof (35)	4,67	4,96	3,15	3,63	7,02	7,49
38. Lent (37)	4,58	4,94	2,00	2,84	7,84	8,31
39. Bijsterhuizen (40)	4,45	4,61	2,55	3,19	6,50	6,80
40. Kwakkenberg (39)	4,32	4,66	2,51	3,29	6,57	6,97
41. Ressen (41)	4,12	4,59	2,33	3,06	6,26	7,20
42. Vogelzang (43)	4,05	4,32	2,83	3,39	6,42	7,29
43. Oosterhout (42)	3,93	4,46	1,63	2,59	6,44	7,37
44. Ooyse Schependom (44)	3,69	4,09	1,70	2,64	7,36	7,49