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Master Thesis in Environmental & Infrastructure Planning

Examining the Effects of Urban Form Factors, High-Integrated Streets, and Topological choice on Bicycle Usage in Rotterdam

by

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Abstract

Urban transportation is a contentious subject; there are many approaches already in use to shift to more sustainable transport options to reduce pollution while offering more space to citizens. Recently, more cities have been considering implementing active transportation like the bicycle. The use of bicycles has many benefits for society, the economy, the environment and public health. The cost to build bicycle infrastructure is relatively low and is one of the few forms of transportation infrastructure that has a net positive affect on society. However, despite the vast amount of literature on which urban form factors encourage citizens to take the bicycle as a mode of transportation, parsing this information remains difficult, leaving policymakers and academics struggling to understand and encourage daily cycling in cities.

This paper examines academic sources and current practices to serve as a benchmark for understanding which bicycle infrastructure designs and space syntax methods currently have the most impact on bicycle usage. This report uses Geographic Information Systems (GIS) and space syntax based on various theories and techniques for analyzing spatial configurations; specifically, it will analyze Rotterdam's urban infrastructure network. In order to understand the street network topological choice, angular integration and connectivity were analyzed using space syntax. The spatial analysis allows for an OLS regression statistical test to pinpoint which combinations of factors play a role in increased bicycle usage. Results showed that areas with a high amount of bicycle infrastructure design and high levels of angular integration and topological choice have a high impact on increasing bicycle usage in Rotterdam. Other results in this study highlight that a cluster of bicycle amenities (transit stop areas, major transit stations and bicycle parking) and a high level of population density also impact bicycle usage significantly. This work adds to the understanding of urban form and which bicycle infrastructure design has the most influence on bicycle counts and provides a few suggestions for policymakers.

Keywords: *Bicycle Infrastructure Design, Urban Form, Built Environment, Street Network Integration, Street Network Choice, Space Syntax*

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List of abbreviations

GIS Geographic Information Systems
OLS Ordinary Least Squares
OVB Omitted Variable Bias

1. Introduction

Urban transportation is a widespread debate that has taken center stage in the planning process for cities. Mobility plays a vital role in city liveability because it allows people to access jobs, markets, recreation, healthcare, and everything else that make life enjoyable (Banister, 2005). In contrast, inadequate transportation solutions create problems for the economy, society, the environment, and spatial efficiency.. A prime example of these issues is that public transportation and automobiles are too expensive, costing more to society than providing benefits, creating inequalities, inaccessibility, polluting the environment, and taking up valuable natural landscapes (Lucas & Jones, 2012). Highlighted in Michael Thomson's book *Great Cities and Their Traffic* (1977), seven problems of urban transport continue to burden cities 44 years after Thomson's book was published. The seven problems are traffic movement and congestion, public transport crowding, off-peak inadequacy of public transport, difficulties for pedestrians, parking difficulties, societal impacts and environmental impacts (Thomson, 1977). Rodrigue (2020) and Tumlin (2012) add that there are many more problems like the growing health concerns of citizens, accessibility, construction and maintenance costs of infrastructure, issues with fare structures, and dominance of the automotive mode in cities. These problems are becoming more complicated as time has passed and, as cities continue to grow, these problems leave academics, policymakers, and citizens to debate what they think is the right approach to our cities' transportation system and urban form.

Over the last 100 years, there has been a considerable amount of change in transportation technology, creating new modes of transportation in the early 1900s (e.g. Automobiles, trams, rapid transit and Light Rail Transit) while improving others in the most recent decade, making them more efficient (e.g. Trains, bicycles, buses, hydration/electric car) (Proost et al., 2002). Yet cities have not changed at the same speed to support, facilitate, and encourage the use of such modes. The automobile now dominates most of the world's cities creating an urban environment that caters exclusively to one method of transport. An environment that is not conducive to active transportation produces unsafe, uncomfortable, and unhealthy travel behaviour. Cities see 30-60% of their space allocated to vehicles, giving them the reign in their environment (Shoup, 2018). This space allocation leaves little room for alternatives and creates a path dependency on automobile infrastructure. This path dependency has been increasingly difficult to change from being automobile-centred to focusing on active transportation modes. The institutional design for automobile usage has already been created and established in the built environment and policy framework.

However, over recent years, there has been a shift in the Global North countries. Governments and decision-makers are beginning to realize the negative externalities of the automobile in their urban environment and are beginning to invest and (re)develop the urban form to accommodate active transportation. Ultimately, the aim is to improve cities by giving more space to citizens for active transportation and sustainable and less costly transport alternatives instead, which could offer a more livable city by enhancing the social and physical domains while reducing pollution (Holden et al., 2020).

Giuliano and Joyce (2005) illustrate that the indirect way of facilitating behavioural change is through structural strategies such as changing the urban form, the transit level of service and the walking/bicycling environments to regulate travel behaviour. These changes in urban form factors result in reducing vehicles in the city have immense benefits on the physical and social environment. Some of the benefits include an increase in transportation alternatives (Pucher et al., 2010), reducing automobile dependency and air pollution. Cleaner air in the cities and more active living by use of active modes of transport means healthier citizens resulting in less fiscal spending on healthcare (Nieuwenhuijsen and Khreis, 2016), more room to socialize in public spaces, creating good social cohesion (van Kempen and Bolt, 2009), and safer streets due to the reduction of cars on the road (Woldeamanuel, 2016). Suppose planners want to create more liveable cities for citizens with some of the listed benefits above. In that case, it is necessary to rethink the urban form to facilitate alternative modes of transport such as cycling.

1.1 Gaps in Research and Academic Relevance

Cycling can solve some of the urban transportation problems as bicycles, and their infrastructure is inexpensive to build and does not require much space. Travelling by bicycle is quicker than other means of transportation in short distances in urban environments and takes low effort from the user for short to medium trips (Heinen et al., 2010). The underlying problem still lies in encouraging users to cycle. There is a broad debate on which urban form factors will best encourage bicycle users in a standardized procedure between governments. There is a need to understand what exact urban factors can influence the usage of the bicycle. These factors can be set as the new standards for bicycle infrastructure planning and design to maximize the benefits of the bicycle. The results of this study can later be emphasized as predominant urban features to aid urban planners and policymakers to encourage potential bicycle usage outcomes when (re)developing street infrastructure.

Gaps in Research

Inconsistencies in the research tend to arise when the methods or the variables used in a study are different from other studies and when studies choose a specific combination of variables. For example, in Zhao et al.'s (2020) study, land use was the primary variable considered resulting in parks, and recreational land uses showing an influence on bicycle usage. However, it could not be concluded if this encouraged bicycle usage in general or if the proximity of a park impacted bicycle usage. The control variables used in the study by Zhao et al. (2020) do not include any urban design factors but only socio-economic variables. When analyzing the literature about the impact of land use and population density, Pan et al. (200) find that land use is only significant when the size of a city is small and dense, as they produce better conditions for cycling as commutes are shorter. On the other hand, other studies show that population density has a crucial effect on bicycle usage; however, when Rybarczyk & Wu (2014) add street integration which is measured with space syntax theories, into their models, population density is significant but has minimal influence.

There are three research gaps in the literature; first, the urban form factors chosen to analyze the effect on bicycle usage regularly overlook important combinations. Some of the combinations that are missing are street configurations (integration, connectivity, choice), urban form (types of bicycle routes, road surface, road speed, bicycle amenities (e.g. proximity to bicycling parking, transit stop areas and parks)) and patterns of urbanization (population density, job density, land use). Although some of these factors have been looked at separately in some studies (Cai et al., 2020; Christiansen et al., 2016; van Mil et al., 2020; Xia et al., 2020), they have not been included together in one combined approach. This lack of a holistic approach might be the missing link needed to explain which factors have the most impact on bicycle use. The second gap is that research does not often look into how urban form factors influence bicycle use; most studies fail to see the value of this practice (Ewing & Cervero, 2010; Gao et al., 2018; Koohsari et al., 2020; Lee et al., 2020; Rybarczyk & Wu, 2014; Winters et al., 2010). The third gap is the oversight in characteristics when choosing which city to analyze urban form factors that affect bicycle usage. Studies either focus on analyzing a North American or sprawling city that has poor bicycle infrastructure with low bicycle culture (Crucitti et al., 2006; Deliali et al., 2020; Ewing & Cervero, 2010; Pucher & Buehler, 2006) or a European city is analyzed with a strong bike culture or one that is highly densified (Fraser & Lock, 2011; Keijer & Rietveld, 2000; Read, 1999; van Goeverden et al., 2015; van Mil et al., 2020; Proost et al., 2002). This third gap leads to disagreements of results that hinder the comparison of different urban form factors that encourage bicycle usage across cities with similar built environments.

On the societal level, bicycles offer individuals an efficient, cheap, healthy mode of transport, thus improving citizens' wellbeing by making it easy and safe to use the urban environment and encouraging citizens to cycle more. Studies from Christiansen et al. (2016), Fraser & Lock (2011), Hunt & Abraham (2007), and Proost et al. (2002) show that cycling has numerous benefits for citizens and governments including healthier citizens, beneficial environmental effects, less stress on the health system, a boost in the economy, and saving costs on maintenance. Cities with a high number of bicycle use have a positive impact on citizens' health; citizens are less obese and indicate more robust physical and mental health (Helbich et al., 2014; Saelens et al., 2003; Winters et al., 2010). These benefits in citizens' health impact the health system, with fewer patients saving the government capital. In some cities, there is a net gain of a few cents for each kilometre of bicycle infrastructure built (Colville-Andersen, 2018). Lastly, bicycle infrastructure is the second cheapest transportation infrastructure to build aside from walking, as it does not require the same amount of materials or maintenance (Colville-Andersen, 2018).

For academia, this study helps to untangle the multicollinearity in the research field of what urban form factors can encourage bicycle use. Previous studies struggle to identify and classify which urban form factors directly affect bicycle usage (Gao et al., 2018; van Govererden et al., 2015; Hull, 2004; Hunt & Abraham, 2007; Pusher & Buehler, 2008; Pasha et al., 2016). Usually, the combination of speed, surface type of the road, and integration with bicycle amenities (proximity to transit, bicycle parking, parks) are left out. Moreover, some studies focus on qualitative analysis to understand bicycle usage with results that have been hard to reproduce in other cities (Hull & O'Holleran, 2014; Liu et al., 2017; Rybarczyk & Wu, 2014; Talihun, Levinson, & Krizek, 2007; van Mil et al., 2020). This study uses a different combination of variables with more advanced spatial analysis methods, such as space syntax. This study attempts to isolate some of the many factors in the discussion on encouraging bicycles as a daily, active transportation mode. It uses urban form factors related to bicycle infrastructure design, choice, and integration levels to understand its relationships with bicycle usage. These isolated factors will identify elements that can be added to future studies creating a more holistic understanding of bicycle usage—creating a new baseline for research when analyzing the impacts of urban form factors, choice and integration levels on bicycle usage.

1.2 Aim and research question of the study

This study aims to identify which urban form factors encourage citizens to use bicycles. In addition, it attempts to understand if bicycle infrastructure design alone provides better results than when it is incorporated with high-integrated street networks. It will use the City of Rotterdam in the Netherlands as its case study.

Thus, the **primary research question** is:

- *Do streets with high network choice and integration with several bicycle infrastructure design elements lead to a higher number of bicycle users?*

The **secondary research questions** this thesis aims to answer are:

- *Do areas with more bicycle infrastructure design have more bicycle users?*
- *What combination of bicycle infrastructure design elements results in the most bicycle usage?*
- *Does high street integration (analyzed by space syntax) result in higher bicycle usage?*
- *Is there an interaction between network integration, choice and bicycle infrastructure design that would lead to an exceptionally high amount of bicycle usage?*
- *How significant is the impact of patterns of urbanization on bicycle usage?*

The remainder of this study is organized in the following manner. Chapter 2 provides the connection to theoretical debates discussing which factors impact bicycle usage in the urban context; it examines built environment factors and patterns of urbanization factors in order to understand the relevant scientific debates and comes up with a conceptual framework that acts as the basis for the hypotheses and the empirical section of this study. Chapter 3 discusses the methodology used for the empirical part of the study; afterward, the chapter delves into the data collected, used, and managed; this will include a description of how the data was analyzed. Chapter 4 describes the results of the empirical research while producing maps for further interpretation. Chapter 5 discusses the results of the empirical research while highlighting the contributions to planning theory and the limitations of the study. Chapter 6 will conclude the thesis by answering the research questions while giving insight into recommendations for policymakers, the limitations of this study, and recommendations for further research.

2. Theoretical Debates

This section reviews and analyzes academic articles and government documents to understand which factors in the urban environment influence bicycle usage. The literature review focuses on the physical environment exploring which factors might influence bicycle usage to develop a conceptual framework for the analysis. This literature review is structured thematically, and relevant articles were selected and divided into three groups: built environment, space syntax, also a component of the built environment, and patterns of urbanization. This structure of dividing the literature is based on the articles by Forsyth & Krizek (2011), Hull & O'Holleran (2014), Liu et al. (2017), Pan et al. (2009), Raford et al. (2007), Rybarczyk & Wu (2014) and van Mil et al. (2020) and played a vital role in the further sub-sections under the three groups. First, there is an overview of urban design, which leads to specific urban environment factors that influence bicycle usage. The most commonly used urban environment factors highlighted were proximity to parks and bicycle parking, integration with public transportation and safety measures like varied levels of protection for bike lanes, the width of bicycle lanes and the speed of roads adjacent to bicycle infrastructure. Next, the thesis will examine less commonly studied urban factors like space syntax as a method that measures syntactical accessibility through connectivity, integration and choice values to help analyze interactions within the built environment. Lastly, it will review the other urban form factors related to patterns of urbanization that impact bicycle usage, focusing mainly on leading influences on bicycle usage like land use, job and population densities. This literature review aims to develop a conceptual framework for this master thesis, which would be used as the basis for the empirical part of the study, acting as the informative component that aids the process in methodology.

2.1 Urban Environment

This review begins with assessing which urban design components can encourage bicycle usage to grasp the situation better. Forsyth & Krizek (2011) and Saelens et al. (2003) mention that urban design is an action as it can change the way people perceive and interact with the built environment. Urban design encourages bicycle usage by changing and improving spatial functions by creating better urban structures with enhanced materials, visual continuity, user experience resulting in a change in societal behaviour (Forsyth & Krizek, 2011). Hull & O'Holleran, (2014) mention that good design plays a critical role in the way the built environment influences bicycle usage highlighting factors such as the design of bicycle paths, wayfinding (signage), the width of bicycle paths, intersection design, lighting of bicycle paths and surface type/quality. Thus, urban design is highlighted as the overarching process of shaping the built environment, creating a safe and attractive space for cyclists (Dovey & Pafka, 2016; Forsyth & Krizek, 2011). According to the literature, the built environment is one of the most critical drivers encouraging bicycle usage. For that reason, the analysis of this thesis focuses on the built environment. The urban built environment and urban design elements play a prominent role as they are strongly connected to transportation decisions like the influence on bicycle usage (Crucitti et al., 2006; Forsyth & Krizek, 2011; van Goeverden et al., 2015; Hull & O'Holleran, 2014; Nielsen & Skov-Petersen, 2018; Rybarczyk & Wu, 2014). Analyzing the built environment allows for a better understanding of the street evolution and movements in a city to help us explain some movement consequences (Jiang & Claramunt, 2002). The relationship between the environment and bicycle usage includes a vast combination of factors producing somewhat mixed results (Zhao et al., 2020). No single variable stands out but rather a combined effect of several variables has the most significant impact on bicycle usage (Ewing & Cervero, 2010; Rybarczyk & Wu, 2014). The following paragraphs will highlight the leading urban design elements in the built environment that influence the number of bicycle users as they are considered in the empirical case study.

Parks and green space

Upon reviewing the literature, one of the strong influences of bicycle usage is the proximity to parks (Hull, 2004; Pasha et al., 2016; Pusher & Buehler, 2008; Rybarczyk & Wu, 2014; Zhao et al., 2020). There are a few reasons for this outcome. Parks and green spaces offering shade tend to cool temperatures for cyclists traveling alongside them and provide a sense of calm in the city (Titze et al., 2007). Cyclists enjoy green environments and often link the proximity of parks to benefiting their health (Fraser & Lock, 2011; Pasha et al., 2016). A large amount of literature on the effects health and recreational activity have on bicycle usage. According to Fraser and Lock (2011), cyclists are concerned with environmental factors that support their wellbeing, such as the proximity of a bike path to green space. Many cyclists commonly choose routes with green areas to be part of their trip. This indicates an urban form factor that has a strong relationship with bicycle users' choice and can influence bicycle usage. However, it is mentioned that many occasional cyclists only cycle to parks as a recreational activity (Pasha et al., 2016; Zhao et al., 2020). It is unclear if these cyclists are frequent or just occasional users. Rybarczyk & Wu's (2014) article shows that there is a significant association between bicycle usage and proximity to parks in their model displaying a relationship to bicycle commute choice. While other studies from Pasha et al. (2016) and Zhao et al. (2020) show that proximity to parks also influences bicycle usage, they suggest this results from occasional users coming to parks for recreational usage. While it has not been proven whether it influences commuting by bicycle, it is something to keep in mind when encouraging daily bicycle usage. Proximity to these areas is crucial to examine as not all distances will increase bicycle usage, but the general rule of thumb for distances individuals want to cycle are one to three kilometres (van Mil et al., 2020).

Bicycling Parking

Amenities for bicycles perform an essential function in influencing bicycle usage as they cater to specific needs, making cycling more accessible, comfortable and safe for the user. Unfortunately, city administrators tend to forget that bicycle infrastructure is not just about the lanes and paths but about the more minor details (Chen et al., 2018). For example, bicycle parking is often a design element that gets overlooked. While reviewing the content on bicycle parking and its influence on bicycle usage, many authors have stated it is an integral element to encourage users. (van Govererden et al, 2015; Hull, 2004; Hunt & Abraham, 2007; Pusher & Buehler, 2008; Pasha et al, 2016). Hull (2004) mentions that frequent and high-quality bicycle parking is needed not just by transportation hubs. Cyclists need parking everywhere they go, by supermarkets, schools, shopping streets and business areas. Furthermore, parking facilities should offer well-lit secure parking as close as possible to the destination. These results show a considerable impact having a significant positive effect on the attractiveness of bicycling to a location (Hunt & Abraham, 2007; Pusher & Buehler, 2008). To further encourage the use of these facilities, Pusher & Buehler (2008) suggest making them a priority for women allowing for safety and creating a few deluxe facilities where one can repair their bicycle and give them the ability to rent a bicycle when in need. Bicycle parking offers cyclists the tools for peace of mind when coming and going to different locations, allowing them to feel safe when parking their bicycles, repairing their bicycles, or simply offering a bicycle to use when they do not have one (Chen et al., 2018). Barberan & Monzon (2016) mention that shorter proximities to bicycle parking from the bikeways would have a more substantial impact on bicycle usage than in the case of amenities and leisure. The cause behind this effect is that people chose walking over biking when parks and bicycle amenities are closer to an individual's home.

Integration with public transport

The integration of bicycle infrastructure with public transit has shown the most substantial impact (Inno-V, 2017) this factor can be classified as a bicycle amenity for this study. Public transportation and the bicycle are a great combination as the bike can get people to the station and then people from a station to a different place. Public transportation gets individuals to their destinations further and sometimes even faster than the automobile (Pucher & Buehler, 2008). Areas with well-integrated public transport and bicycle infrastructure see higher numbers of bicycle usage, allowing individuals to coordinate with public transportation (Hull, 2004; Pasha et al., 2016; Zhao et al., 2020). If bicycle infrastructure is not integrated properly with public transportation systems, users will opt for other modes. Ultimately producing and perpetuating automobile-dependence as the users of potent public transportation might either take the automobile to the transit location or all together will opt for the automobile over public transportation (Vugt et al., 1996). Van Mil et al. (2020) concluded that bicycle and transit networks' integrated design is precious when increasing multimodality. Coordination with public transportation can include bicycle parking facilities, wayfinding, allowing for bicycles on public transit vehicles, bike lanes that lead to, or even into, transit stations (Pasha et al., 2016). It is vital to mention that different types of public transportation mode areas see different bicycle usage levels; small transit stop areas like bus/tram stops or connections have lower amounts than larger train stations or terminals (van Mil et al., 2020). This is because transit stops tend to be closer to the individual's home and do not require a long walk to access, where larger terminals/stations of trains, ferries and airports will not be near an individual's home and will require other modes to reach. Nevertheless, it is crucial to consider the proximity to these areas to allow for a threshold to determine optimal effects. Keijer & Rietveld (2000) and van Mil et al. (2020) stated that the comfortable proximity for cycling to larger transit stations is generally between 1 to 3km, and for small stops closer to home, between 800m and 1.2km.

Safety Measures

A mode of transportation requires several elements to become suitable for the masses; it needs to be user friendly, cheap, healthy and safe to use. Biking and safety is the most discussed topic in the field of the built environment. Safety is arguably the most influential component on bicycle usage because, put simply, when people do not feel safe riding bicycles, they choose not to.(van Govererden et al., 2015; Hull, 2004; Pasha et al., 2016; Pusher & Buehler, 2008; Pucher & Buehler, 2017). When looking at how safety affects cycling, many factors influence usage policies; drivers' behaviour, cyclist perception, and the built environment. When it is safe to use the bicycle because of the physical environment, it encourages more users who are not "cyclists" per se (Deliali et al., 2020).

The following will only examine the built elements that relate to safety and the influence of bicycle usage. Protected bicycle infrastructure is the easiest way to increase safety and its perception (Hull, 2004).

Protected with a large buffer or separated with a curb, bicycle routes were found to be one of the strongest influences for bicycle usage (van Govererden et al., 2015; Hull, 2004; Krizek & Roland, 2005; McNeil et al., 2015; Pucher & Buehler, 2008; Pucher & Buehler, 2017; Titze et al., 2007). Giving users a feeling of safety and comfort, as they are given their own space away from the traffic that has vehicles driving at quicker speeds and parked cars that open doors sporadically (Deliali et al., 2020; van Govererden; Hull, 2004; McNeil et al., 2015; Zhao et al., 2020). Protected or separated bicycle routes act as a barrier from vehicles and pedestrian traffic; studies show women are more likely to bike and bring their children cycling if there is adequate protection from automobile traffic (McNeil et al., 2015). Protection from automobile traffic is integral to increasing the numbers of daily riders and commuters. Building upon the idea of protected or separated bicycle infrastructure, it is essential to note that protected intersections for cyclists rank highly in the encouragement of cyclists (van Govererden et al., 2015; Deliali et al., 2020; Nabhan, 2014). These protected intersections are designed to allow both users to have their separated areas which minimize conflict zones while improving sightlines from each other (Hull, 2004; Pucher & Buehler, 2008). Protected intersections tend to prioritize bicycles, making it quicker for cyclists to pass through the intersection rather than automobiles. Pasha et al. (2016) add that the size of an intersection also plays a role in the number of users as the larger the intersection, the more hazardous the location would be, and smaller in size intersections are favourable (Pan et al., 2009; Pasha et al., 2016). Smaller intersections are encouraged as the traffic is funnelled into a smaller area allowing for better eye contact to develop between users (Deliali et al., 2020).

Having the right amount of space can mean a great deal when it comes to cycling; it can allow for a safe distance from cars, accommodate the sheer number of commuters or allow cyclists to bike beside a friend or child (van Govererden et al., 2015; Hull, 2004; Hunt & Abraham, 2007; Marshall, 2005). It is suggested that a minimum of 1.5 meters is given, but 2.5 meters should become the new standard. Overall the more width a bike lane has, the more attractive it becomes to bicycle users (Hull, 2004; Marshall, 2005). Ensuring that cyclists feel safe when using their bicycles is a reliable approach to guarantee an impact on bicycle usage (Deliali et al., 2020).

2.2 Space Syntax

Researchers are becoming more interested in extracting additional structural and movement details from urban street networks. Traditional analyses, which only use GIS network analysis, are unsuccessful in exposing the nuances of the structural patterns of an urban street network. GIS can perform several spatial analyses, like queries and reasoning, measurements, transformations, and optimization, but it lacks the computing power and theories to examine street network connectivity, choice and integration levels. Instead, in space syntax, a different perspective is taken on the structure of an urban street network, emphasizing its topological structure, using spatial configurations to understand a street-to-street relationship, which is the primary research object in space syntax. When examining the literature, many academics use space syntax based on theory and methodologies from Bill Hillier (2007). This facilitates the translation of the physical environment into quantitative information, allowing for a quantifiable analysis of the objective urban fabric (Raford et al., 2007; Rybarczyk & Wu, 2014; Pan et al., 2009). Based on Hillier's (2007) book *space as an aspect of social life*, there are a few elements to space syntax in urban studies. It is a collection of methods and techniques for analyzing cities as spatial networks created by the placement, grouping, and orientation of buildings. These methods enable researchers to examine how a street connects to all other streets in a large city spatially (Nes & Yamu, 2018). Space syntax offers a range of analytical methods for studying how spatial networks apply to functional movements such as vehicle and pedestrian travel, bicycle flow patterns, land use patterns, area separation, crime dispersion, property values, migration patterns, and even social welfare and malaise (Koohsari et al., 2020; Raford et al., 2007; Rybarczyk & Wu, 2014). These approaches and strategies have been implemented in various cities around the world, adding to the database of cities that have been analyzed using space syntax. Finally, theories and conceptions of how cities are spatially constituted offer an understanding of how urban space acts as a generative force for societal and economic activities and cognitive factors.

Space syntax's set of theories is based on mathematical logic, which analyzes spatial ordering in various ways. It allows for characterizing the functional patterns of urban space rationing to the pattern that illustrates three different measures: integration, choice, and depth, each providing a different understanding of the urban fabric.This section of the literature review will focus on the measurement of integration and connectivity within cycling networks using space syntax.. Hillier et al. (1993), McCahill & Garrick (2008), and Raford et al. (2007) emphasize that there is a relationship between active travel behaviour and connectivity and integration, mentioning these methods can be applied to the research when identifying which built environment factors influence bicycle usage.

2.3 Connectivity

Connectivity concerns itself with the level at which streets are connected or interconnected; this can explain the continuity of a network (Marshall, 2005). It is the number of lines that are directly related to a given line. Connectivity looks only at the links in a network and asks how many potential connections can be made from each segment in a street network to all other segments. Lines with high connectivity values are thought to be more commonly used than other lines and draw more general traffic. Human activity patterns can be anticipated to a degree based on this thinking. Marshall (2005) states, "To a significant extent street pattern is – and must be – influenced by the geometry of movement and the topology of route connectivity" (Marshall, 2005, p, 13). Therefore, understanding the level of connectivity can help researchers identify the different levels of connectivity a street possesses. This information can be used as a control variable to isolate other factors when analyzing the built environment to assist in the understanding of bicycle usage. Furthermore, street connectivity is recognized to positively impact bicycle usage because higher street connectivity provides more route options, resulting in a significant reduction in trip distances (Jiang & Claramunt, 2002; Pasha et al., 2016; Zhao et al., 2020). However, connectivity does not completely explain movement, as different types of urban elements like land use, infrastructure, and built environment interplay with the level of connectivity (Pafka et al., 2020). The usage of connectivity in this study may lead to limitations in interpreting the reasons for movements.

2.4 Spatial Integration

Integration is a method of calculating the number of street transitions needed to access all other street segments in a network using the shortest paths (Hillier, 1996; Hillier & Hanson, 1984; Teklenburg et al., 1993). Studies from Turner (2007) and Hillier and Iida (2005) show that integration analyses are more suitable for predicting human movements in space syntax than connectivity. Integration measures, unlike connectivity, measure the most straightforward paths, which can be viewed as fewest turns to reach all other streets or, for this purpose, the shortest path in the street network (Hillier, 1996; Hillier & Hanson, 1984). While the level of connectivity doesplay a factor in the flow of movement, alone it does not explain or result in an ease of movement. Connectivity only shows the level of connection a street segment has, not more; in the broader sense, it explains the accessibility of given street segments adjacent to it. Connectivity, however, does not explain the ease or how integrated a street segment is with the whole network.

There are three methods to evaluate the level to which streets are integrated using three different distances within the integration measures: metric distance, topological distance, and angular distance. Topological distance calculates the number of turns from one street to another (topological integration highlights areas with the fewest turns), angular distance (geometrical), analyses the angular change from one space to another (this is useful when looking at spaces or roads that have high angularity) and metric distance calculates the Euclidean distance (the shortest mathematical distance) in meters from one space to another (Hillier, 1996; Hillier & Hanson, 1984). When investigating the three integration measures from space syntax, angular analysis and topological analysis are more advanced than metric analysis. Metric distance only concerns itself with the distance factor (shortest mathematical distance). Thus, the measure fails to analyze the nuance in the urban environment, such as positions of buildings, curves in the road, or highly dynamic street networks (Turner, 2007). However, angular distance has shortcomings that should be highlighted. Angular measures might over-calculate the roads that would be particularly curvy, whereas topological choice can account for this as it calculates the fewest turns.

2.5 Choice

Choice is the extent to which a given street belongs to the shortest path between a pair of two streets in a network. When a street has a high choice value, many of the "shortest paths" pass through it (through movement) (Sharmin & Kamruzzaman, 2018). Topological choice represents the way humans travel and describes more than just the connectivity of different areas in an urban area. Hence, using choice values from space syntax can help researchers further understand relationships between the urban environment and street travel choices. Thus topological measurements in a choice analysis can explain a more natural human travel versus angular distance. It pinpoints the shortest paths topologically that have the least amount of turns which intersect at multiple points. Angular change is a crucial factor when analyzing street segments that are not straight, and the angular distance may over or underweight curved roads. This change of direction also differs from the Euclidean distance, as humans cannot always take the shortest path on roads because of obstructions and soft barriers like fences, streetcar tracks, and traffic lanes. Hillier & Iida's (2005) study outlines that topological complexity is critically involved in navigating urban grids. Angular and metric integration is unlikely to be the best criterion for navigational decisions. The issue remains unsolved because no mechanism for extracting cognitive knowledge from aggregate flows exists (Hillier & Iida, 2005).

A combination of angular integration and topological choice analysis might provide a more accurate analysis of the built environment catching the nuances that the metric measurement would miss. In Rybarczyk & Wu's (2014) and Koohsari et al.'s (2020) study, angular integration values and behavioural choice (behavioural choice can be simulated with topological choice analysis) display the most substantial influence in bicycling decisions (Koohsari et al., 2020; Rybarczyk & Wu, 2014). Some studies, however, have discovered a connection between integration values and other built environment factors, including land use and population density. According to the analyses by Lee et al. (2020) and Xia et al. (2020), areas with higher integration levels often have higher land use mix values. Since mixed land use combines residential, industrial, cultural, institutional, entertainment or other features used in a single location that meets people's daily needs in close proximity; commuting distances are significantly reduced, allowing for more bicycling (Zhao et al., 2020). The study mentioned above suggests then that integration values and other built environment factors can interact somehow. As a result, it would be worthwhile to investigate whether integration and choice values impact bike use alone or in conjunction with other urban-type factors.

2.6 Patterns of urbanization impact on bicycle usage

To better understand the factors that might influence bicycle usage, it is integral to also look at the patterns of urbanization that have an impact. This section will look at the most commonly stated impacts from the literature. Studies from Cai et al. (2020), Ewing and Cervero (2010) Faghih-Imani et al. (2014) and Rybarczyk & Wu (2014) concluded that population density, job density, and land use are all critical factors affecting bicycle-sharing ridership.

In Ewing and Cervero's (2010) article, population density is identified as a primary determinant of urban travel while mentioning that the density of business areas is as important as the density in residential areas (Ewing and Cervero, 2010). Highly dense business areas are said to make travel distances short, as individuals will have greater access to one area; this can make cycling more attractive. Cai et al. (2020) agrees with this and adds that population density and residential land use have positive effects because they create a more positive experience, ultimately improving bicycle usage. Other studies from Faghih-Imani et al. (2014) state that the population density around transit stations also positively affects bicycle flows. Higher densities around transit stations make it more efficient to run more services, creating further ease and freedom when using a public transit system, which results in excellent transit systems attracting more commuters to combine transit and the bicycle because the bicycle is used for the shorter distance of the trip. In contrast, transit is used for the longer trip sections (Faghih-Imani et al., 2014). However, this does not appear to be the case once other variables are controlled (Ewing and Cervero, 2010). Similar findings have also been made and stated that population density is significant in their model but displays a minimal influence on bicycle usage (Rybarczyk & Wu, 2014).

When further examining which patterns of urbanization impact bicycle usage, it is suggested that the interrelationships between land-use and travel behaviour are affected by urban form variables but do not result in a direct effect (Hull, 2004; Pan et al., 2009; Zhao et al., 2020). Faghih-Imani et al. (2014) mention that areas with restaurants, other commercial establishments, and colleges significantly impact the arrival and departure numbers. Hence a further examination of land use and urban form should be considered. Studies that consider different land uses conclude that mixed-land uses encourage the communing of non-automobile modes (Cervero, 1996; Chillón et al., 2016; Pan et al., 2009). In addition, Pan et al., 2019 stated that their findings show that planning codes need to promote small street blocks; this can be interesting to explore further while analyzing.

When investigating job density, Vandenbulcke et al. (2011) state an increase in bicycle usage when job density is higher; this can directly affect the commuting distances of bicycle trips. However, it is suggested that this is linked to the size of a city, correlating it with compact conditions and tight city networks, which stimulate cycling. Vandenbulcke et al. 's (2011) findings make rational logic as the size of a city can affect the distances travelled on a bicycle, making it faster or easier to travel within a city but does not give a direct result of job density. When comparing bicycle usage in the US and Canada, Pucher & Buehler (2006) found that cities with higher job densities resulted in higher bicycle usage. They conclude that density is the most significant factor when encouraging bicycle usage. However, there are some inconsistencies with that statement; Harms & Kansen (2018) explore a comparison between New York City in the United States of America with Groningen, a city in the Netherlands that shows exciting results. The results show that New York City has a low amount of bicycle usage while having both a very high population and job density. On the other hand, Groningen has a low population and job density, but for the past five years, it had an average of 60% of bicycle mode every year (Harms & Kansen, 2018). Thus, it is not conclusive to say that density alone is the main factor in bicycle usage. These outcomes are precisely what Saelens et al. (2003) have concluded, finding that communities with a combination of higher density, more street connectivity, and more land use mix report higher rates of walking/cycling.

Pasha et al. (2016) state that despite the importance, little research has been done to examine the interactions between different land uses population, job density and urban form components (connectivity, integration, and bicycle design elements) on the influence of bicycle usage. Concluding from Pasha et al. (2016) results, this study deduces that to understand the urban form better, it is critical to control for the influence of land use, population density, and job density when looking at the effect of other urban form factors (such as bicycle infrastructure design, choice and integration values).

Despite several studies that have found positive associations between the built environment and bicycle as mode choice (van Govererden et al., 2015; Hull, 2004; Hunt & Abraham, 2007; Pusher & Buehler, 2008; Pasha et al., 2016), few have been able to disentangle the link between urban form and bicycling usage (Raford et al., 2007, Rybarczyk & Wu, 2014). This may be due to minimal attention to several urban form factors (Rybarczyk & Wu, 2014). These factors include the presence of parks, green spaces, bicycling parking, integration with public transportation, the width of roads and paths. The syntax of road networks can look at the connectivity, choice or integration; other components include patterns of urbanization like job density, population density, and land use mix. Other arguments for why academics have not completely pinpointed which factors impact bicycle usage is because using the bicycle as a mode of transportation is also influenced by socio-demographic factors (e.g. gender, age, income, etc.) (Handy et al., 2010; Ramezani et al., 2018). This literature review finds gaps in academic literature regarding the exact reasons why individuals use the bicycle (Forsyth & Krizek, 2011; Liu et al., 2017; Pasha et al., 2016: Saelens et al., 2003). In particular, it is difficult to pinpoint which exact indicators of the urban environment encourage individuals to use the bicycle as a daily mode of transportation (Forsyth & Krizek, 2011; Hull, 2004; Liu et al., 2017; Nielsen & Skov-Petersen, 2018; Rybarczyk & Wu, 2014).

This research elaborates on the findings of several studies from academia which have focused on design indicators, spatial analyses like space syntax, in addition, to other patterns of urbanization like land use, population and job density (Forsyth & Krizek, 2011; Hull & O'Holleran, 2014; Liu et al., 2017; Pan et al., 2009; Raford et al., 2007; Rybarczyk & Wu, 2014; van Mil et al., 2020). Many studies were more qualitative, with areas chosen that were not so clear and only covering small areas in a city that can be left to different types of interpretation (Hull & O'Holleran, 2014; Liu et al., 2017; Rybarczyk & Wu, 2014; Talihun, Levinson, & Krizek, 2007; van Mil et al., 2020). Despite its significance in urban transportation and land use planning, there has been little research on the impact of different urban form configurations and street patterns on bicycle usage (Pasha et al., 2016).

This study will build upon the findings of Forsyth & Krizek (2011), Hull & O'Holleran (2014), Liu et al. (2017), Pan et al. (2009), Raford et al. (2007), Rybarczyk & Wu (2014) and van Mil et al. (2020) while also taking a different approach to the matter. It will input both qualitative and quantitative factors that have shown to impact bicycle usage and quantitatively examine the variables for a whole street network of a city. Rotterdam, the city chosen, has more characteristics of a North American or a sprawled city. However, it is located in The Netherlands, a country with the strongest bike culture across the globe. This context can offer exciting results, which can be implemented in cities with similar characteristics in the hopes that the results can increase bicycle usage. Quantitative methods provide a more manageable and accessible way to analyze the whole network of the city as a large amount of data is gathered and then analyzed statistically. As a result, it can erase many biases, and if researchers were to run the analysis on the data, they would always end up with the same results in the end. Quantitative methods can allow for there to be more accurate and objective results. When processing the data, it is more transparent; the variables are direct numerical or basic text observations, not subjective viewpoints from individuals, producing more reliable results than qualitative research (Bryman, 2012). Furthermore, the researcher has more control over how the data is gathered and is more distant from the experiment producing a scientific analysis of the built environment (Bryman, 2012).

This study contributes to the literature by identifying which bicycle infrastructure design can encourage citizens to use bicycles. Bicycle infrastructure design is focused on design features that either make up the bicycle pathway/roads (e.g. separated bicycle lane, protected intersections, type of surface or speed) and/or design features around the bicycle pathway/roads (e.g. parks, bicycle parking, the type of land use in the area or population density). These aspects mentioned above are generally accepted as exceptional design methods (Hull & O'Holleran, 2014; Nabhan, 2014) compared to others, such as painted bike lanes, bikes lanes beside parked cars where the driver exits, bike lanes on side streets that do not interact with the automobiles as much, unprotected lanes, or poorly integrated intersections where most collisions occur as there isn't a clear distinction between different modes of transportation (Orsi et al., 2017). These higher quality types of infrastructure produce higher results, therefore becoming a standard when analyzing and building bicycle infrastructure. Furthermore, this study aims to examine whether bicycle infrastructure design provides better results when incorporated with a high-integrated and choice street network (according to space syntax analysis). Lastly, it aims to view which interactions between variables may explain an increase or decrease in bicycle usage. This examination can help governments isolate which factor(s) in the urban environment can best serve to encourage cyclists from a purely physical approach in the hopes of creating a list of factors to guide the (re)development of bicycle infrastructure.

2.7 Hypotheses of this study

Based on the literature in this field of research, it is expected that this study will find an increase in bicycle usages in areas with high integration and urban design components. These expectations are based on a few other studies like the articles from Forsyth & Krizek (2011), Hull & O'Holleran (2014), Liu et al. (2017) and Saelens et al. (2003). Looking deeper into the space syntax outcomes, it predicted that higher levels of connectivity in street segments would have marginal effects. Connectivity shows the accessibility of street segments in a network and will influence bicycle usage as users favour accessibility (Saelens et al., 2003). Further, angular integration is predicted to show a low amount of influence on bicycle usage. This is because angular integration measures geometric distances in a network and does not calculate street or path nuances that might influence a cyclist's route choice. On the other hand, topological choice is expected to have more of an influence because it calculates the amount times the easiest paths intersects highlight the most through movement, which is more aligned with how individuals traverse the urban street network (Colville-Andersen, 2018: Crucitti et al., 2006; Hillier & Iida, 2005).

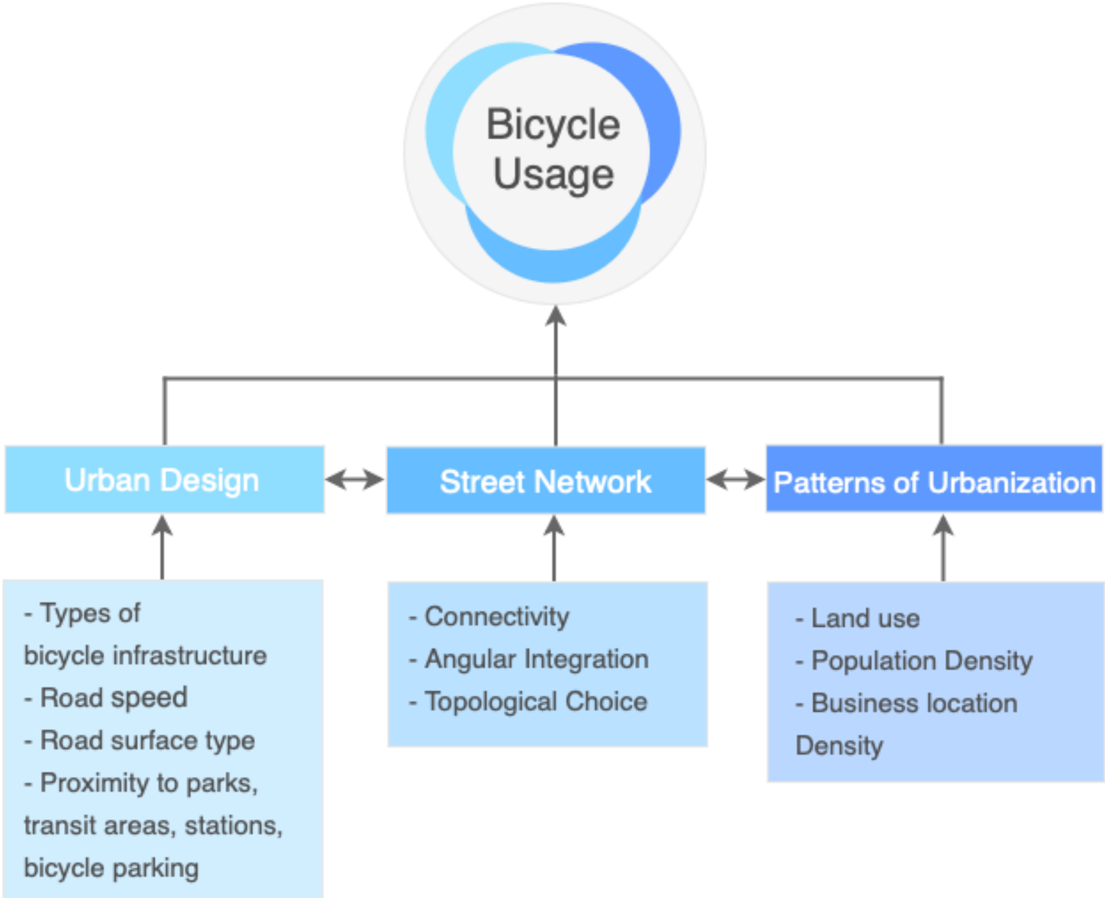
In terms of what outcomes urban design components have, it is anticipated that bicycle routes protected from traffic will have the most significant impact on bicycle usage. These results in bicycle usage in line with the literature suggesting that these areas make bicycle users feel safe and create an ease of use (user-friendliness) (Colville-Andersen, 2018; Crucitti et al., 2006; Forsyth & Krizek, 2011; van Goeverden et al., 2015; Hull & O'Holleran, 2014; Nielsen & Skov-Petersen, 2018; Rybarczyk & Wu, 2014). When looking at amenities that have influenced bicycle usage, transit and parks should have the highest impact on bicycle usage. When reviewing the literature, transit hubs attract and transit hubs with bicycle parking. Both have shown importance in bicycle usage; however, a transit hub with bicycle parking shows an even higher impact on bicycles.(Christiansen et al., 2016; Ewing & Cervero, 2010; van Mil et al., 2020). Areas with parks should demonstrate high levels of bicycle count as they inherently attract individuals for leisure and relaxation in an urban context (van Mil et al., 2020). Lastly, it is anticipated that speed will play a significant role in the number of bicycles on the street; as speed decreases, there will be a more considerable amount of bicycle usage (Deliali et al., 2020).

When observing patterns of urbanization positioned by the theoretical debates on land use should show mixed or low influenced results; this is because land use may only demonstrate a piece of minor evidence to the influence (Xia et al., 2020; Zhao et al., 2020). Land use alone will not be sufficient without a high population or job density because land zoning does not attract people. At the same time, population density or job density is predicted to influence bicycle use significantly as it can contribute to short commutes, which encourages bicycle usage.

2.8 Conceptual Framework

In order to determine the relationships between all the above-described aspects related to bicycle usage, a conceptual model is created and presented in Figure 1, which is based on the theoretical debates that were reviewed. The model represents a simplified schematic of three main topics from the literature that could be examined to explain bicycle usage. Urban design, street network, and patterns of urbanization represent overarching topics with gaps and inconsistencies in the literature. The three research gaps of the combinations of variables, including bicycle infrastructure design and the characteristics of a city when choosing a case study. The inconsistencies tend to arise when the combination of variables is different from other studies or when studies leave out other variables for different reasons. As shown in the model, the three sets of main factors interact with each other. The population density of an area may well result from the composition of the area's built environment, including its land uses, street configurations, and design features. This interaction can also go the other way that design features result from the densities in an area; this is why the other elements are included to control main variables. Within these three sets of primary factors, a few factors were highlighted to influence bicycle usage. Urban design factors include proximity to parks, bicycle infrastructure, protected intersections, road speed, proximity to bike amenities, and proximity to transit locations. Street networks will encompass connectivity, angular integration, and topological choice. Patterns of urbanization include land use, job density, and population density. These factors represent independent variables, and the conceptual model shows the relationships between a series of independent variables and the dependent variable, which is the number of bicycle counts in Rotterdam. The study will go over the variables in the conceptual model and the analytical approach in the methodology section.

Figure 1 Conceptual Framework



3. Methodology

This section describes the case selected for the research and why it was chosen, further elaborating upon the research methods used in this study. Next, this chapter discusses the data collection and data analysis process of this research.

This exploratory study seeks to examine the impacts of built environment factors on bicycle usage. This combination has previously been studied, but outcomes on which factors had a more significant impact upon bicycle usage were mixed. A quantitative approach is best suited here because the study focuses on the complexities of the phenomenon and combines a large amount of data into a comprehensive conception. Hence, this study allows for a more in-depth understanding of the relationship in an academic context that has not been well-established. Researchers emphasize bicycle usage's dynamic and multifaceted essence, stating that a quantitative analysis approach appears appropriate as it allows for objectivity and accuracy (Chen et al., 2018; McCahill & Garrick, 2008; Pan et al., 2009; Xia et al., 2020).

In order to understand how the built environment impacts bicycle usage in practice, a case study is conducted. According to Yin (2014), a case study is an in-depth examination of the complexity and uniqueness of a specific project's strategy, organization, program, or framework in a 'real life' sense from multiple perspectives. Furthermore, a case study allows researchers to investigate the particular factors of a specific city, like the built environment that influences the nature of bicycle usage in a specific context. Yin (2014) mentions that results can not be directly generalizable; though, Flyvbjerg (2006) adds that this does not exclude them from contributing to the collective phase of information acquisition in a given area or society. As a result, gaining a new perspective on the diverse built environment can only help broaden our comprehension of the determinants of bicycle usage, resulting in a deeper understanding.

3.1 Background of the Case Selection: Rotterdam

The City of Rotterdam was chosen as the city for the case study because it met the four criteria of a suitable city to test the conceptual model. These criteria are its built environment, prominent car position, design standards and bike culture. After the Second World War, Rotterdam was destroyed, forcing the city to rebuild its urban centre according to modernist standards (Daamen, 2010). Wide and fast-moving highways, higher buildings, lower densities in neighbourhoods, and growth away from the city centre are similar to those seen in North America. The built environment makes the case easier to be compared to larger North American cities, which very rarely have the composition or densities of European cities. Due to the built environment, the city has a high car prominence, according to Helbich et al. (2014); this is because of the longer distances in Rotterdam, resulting in a greater car dominance and disadvantaged bicycle position. The municipality recognizes the advantages of slower modes with livability, durability, and physical activity while acknowledging the importance of automobile accessibility in Rotterdam (Gemeente Rotterdam & Goudappel Coffeng, 2017). Rotterdam, like other municipalities, employs Duurzaam Veilig (Sustainably Safety), which focuses on infrastructure (networks and high-accident zones), behaviour (steering by design and teaching), and monitoring (Stadsregio Rotterdam, 2003). The city uses national standardized bicycle infrastructure and design, which is the best in the world (van Goeverden et al., 2015). Lastly, and perhaps the most critical and related to the criteria above, the Netherlands has a strong bicycle culture. Bicycle culture refers to cities and countries that encourage a high proportion of practical cycling. Using the bicycle is a way of life in the Netherlands. It has integrated itself into many aspects of the Netherlands. New housing must have space to store bicycles, train stations have massive bicycle parking garages, subsidizing commuting, and comically the Netherlands has more bicycles than people. These four criteria allow for the comparison of a built environment that has been shaped like a city that has been built in the 19th-20th century while at the same time having the expertise, design and infrastructure of a country that has the most bicycle mode share in the world, the Netherlands. These criteria are interesting to the study because they provide diverse built environment characteristics, some of which may support and some may not support bike usage. In contrast, it is located in a country with a biking culture to see if certain built environment factors still influence bike usage in such a biking culture.

3.2 Data Collection

For the data collection, the research strategy that is used is provided in Figure 1. All data is secondary and collected through Open Street Maps OSM (an open-source geographical database where institutions and governments send Geodata to provide free data to the masses), the City of Rotterdam, and the Netherlands Central Bureau of Statistics. Geodata is a term that refers to data and information that has an implicit or explicit relationship to a location on Earth. The data is organized into five categories: street segments, types of cycle paths, amenities, population density/business density and land use. This represents a theme where several variables fall into. These will be explained in further detail below.

Street Segments, Speed, Road Surface Type

The data received from the City of Rotterdam was the entire street network of Rotterdam, which has been divided into street segments; these segments are based on Rotterdam's configurations in that each portion is located between two intersections. This street network is later used as input for the syntactical analysis using space syntax theories and software (depthmapX 0.50) to output levels of connectivity, angular integration and topological choice for each street segment in the city's network. Geographical data (speed of the road, surface type) was also provided in the City of Rotterdam's Mobility Department dataset. In addition, this dataset incorporated bicycle count data for every street/path segment in 2016. Bicycle count numbers represent the dependent variable of this study used in the regression model to analyze the relationship between urban form factors and cycling counts. It has an accuracy of plus or minus five cyclists; the data was corrected with the city's own modelling methods. These methods to modelling the cycling counts were not given with the data, as it is their proprietary model, which they do not wish to release to the public. The dataset also includes the type of surface that the road or cycle path is built from and the speed of the road. The road surface classifications are asphalt, stone tiles, interlocking, gravel, and unpaved and shell paths. All the types were coded into dummy variables, and shell paths were dropped from the model as it becomes the reference group during dummy encoding for regression and is redundant. The speed of the road/ path data includes the speed of the road and the speed beside a separated cycling path. The speed classifications are in kilometres and represent the maximum allowed speed: 0, 15, 30, 50, 60, 70, 80, and 99. The speed of roads and the type of surface each have been represented as factors that makes up one of the primary vector of independent variables.

Types of cycle paths

This section of data includes a few different sets regarding types of cycling paths. All the data was acquired from open street maps and cross-referenced with the data set given by the City of Rotterdam. The five cycling paths in this dataset include 1. The bikeways are either beside roads separated with over a meter buffer (e.g. median, planters, parked cars or concrete barrier) from vehicle traffic or constructed as a path away from automobile traffic (e.g. through parks or beside canals), 2. The bike lanes separated only with a small curb, 3. Roads that allow cyclists to go in the opposite direction on a one-way street, 4. Bike paths on the road but with only a painted lane, and 5. roads that are shared with all modes of transportation. These sets were combined with the data of the number of bicycle counts from the city of Rotterdam in GIS. Each of these types was coded as a dummy variable. Number 5 was dropped from the model as it becomes the base for categorical variables during dummy encoding and is redundant. These five types of bicycle infrastructure have a high impact on providing a feeling of safety for cyclists, which have been shown to influence bicycle counts (Hull & O'Holleran, 2014; McNeil et al., 2015; Nabhan, 2014; Pucher & Buehler, 2008).

Amenities

As stated in the literature review, a few primary elements are related to the built environment that encourages bicycle usage. Four variables have been extracted from these elements that this study will examine: public transit stop areas, major transit stations, parks, and bicycle parking and will be grouped as bicycle amenities in the study. Data for amenities was retrieved from OSM and represents point shapefiles of the geo-locations of the amenities. Public transit stop areas represent transit stop areas on the street for train, metro, tram, bus, and ferry. Public transit stations represent major metro and train stations; this variable can be viewed as highlighting large transportation hubs. Parks are mainly categorized as parks but include small green spaces in neighbourhoods where individuals can enjoy. The variable of bicycle parking is a location with a large amount of bicycle parking, either indoors or outdoors. These parking locations are around stations, institutions, and popular areas like shopping, business or recreational areas but not classified as shared neighbourhood parking. These factors were chosen as the literature shows they significantly influence bicycle counts (McNeil et al., 2015). In order to analyze these variables, they have been separately calculated with proximities; the proximity measurement was created in GIS and linked to each applicable street segment with the amenities proximity. In GIS, this is done using a buffer tool to create a buffer around amenity points and then an intersection tool to intersect it with the street segments to analyze which segments are in close proximity to these amenities. There is a buffer radius around the location and are as follows: bike parking has 400 meters, public transit area has 800 meters, major stations have 1400 meters, and parks have 500 meters. The distances of the proximities are based on the literature. The distances mentioned above were reduced to a count for Euclidean distances as GIS created circle buffers around the amenities and would otherwise represent proximity inaccurately. There is a problem with Euclidean distance measures as individuals cannot travel through buildings and thus must travel around blocks and obstacles. Each of the variables was coded into a dummy variable. These sets were joined in GIS with the street network data from the City of Rotterdam.

Population Density/Business Density

A detailed geometry file of population density, the number of businesses and hectares per neighbourhood is taken from the national Centraal Bureau voor de Statistiek (Central Bureau of Statistics); the data is from 2016 to match the data received from the City of Rotterdam. The data is classified into district and neighbourhood proportions from the proportions created by civil, municipal boundaries of the Land Registry derived from the Key Register Land Registry (BRK). The boundaries between land and water are according to the demarcation of the soil use and the accompanying critical figures for districts and neighbourhoods from Statistics Netherlands. It contains original coordinates and is not generalized. The numbers of businesses and hectares per neighbourhood were divided in GIS to reach the business location densities for each neighbourhood, which was done to simulate job density. In GIS, the data sets of business density and population density have been joined and intersection process linking each street segment data mentioned above. These data sets are used as control variables for the regression model. These control variables were chosen as multiple studies show that population density is a significant predictor of urban travel, with the caveat that business area density is just as essential as residential area density (Cai et al., 2020; Ewing and Cervero, 2010; Rybarczyk & Wu, 2014).

Land Use

The data for land use taken from the national Centraal Bureau voor de Statistiek (Central Bureau of Statistics); is categorized as large areas within neighbourhoods; the categories include retail, industrial, residential, commercial, recreational, parks, and green space with vegetation. Ramezani et al. (2018) noted that literature on land use mix had shown controversies regarding the influence of land use mix on travel behaviour resulting in a lack of predictability. Ramezani et al. (2018) highlight that three joined combinations of land uses represent land use areas that impact sustainable modes of transportation: Residential and commercial, residential and recreational, and residential and recreational and commercial. Thus the only variables used from the total land use dataset will only be residential, recreational and commercial land use combined to simulate practical land use analysis. The three land use data sets will be joined with GIS to three combinations illustrated by Ramezani et al. (2018). Once this data has been joined into three data sets, it is intersected with the Rotterdam street segments data as a dummy variable resulting in each segment classified as one of the three land uses combinations mentioned above.

The theoretical debate above has discussed a variety of factors that have a role in impacting bicycle usage. Nonetheless, a few have not been included in the study as there was no access to the data. The data is inaccurate, missing for the observed time period, or merely not provided to the public. Below is a summary table of the variables that will be used in this thesis.

Table 1 Summary Table of the Variables used in the OLS Model

Summary Table of the Variables used in the OLS Model		
What is it	*How it was calculated*	*Data explained/ Unit of measurement*
Speed	GIS intersected speed with street network, finally export into final data set, continuous variable	On street road speed / Km/h
Proximity to parks	GIS a buffer of 500 meters was created around parks, then intersected with network to see if a segment is located in this buffer, finally export into final data set, dummy variable (values of 1 if segment is located in the buffer, and 0, otherwise0.	Parks and green spaces / Proximity of 500 meters
Proximity to transit stop areas	GIS a buffer of 800 meters around the location was created, then intersected with network, finally export into final data set, dummy variable (values of 1 if segment is located in the buffer, and 0, otherwise).	Transit stop areas for trains, metro, tram, bus, and ferry / Proximity of 800 meters
Proximity to bicycle Parking	GIS a buffer of 400 meters around the location was created, then intersected with network, finally export into final data set, dummy variable (values of 1 if segment is located in the buffer, and 0, otherwise).	Parking designed specially for bicycles / Proximity of 400 meters
Proximity to major transportation stations	GIS a buffer of 1400 meters around the location was created, then intersected with network, finally export into final data set, dummy variable (values of 1 if segment is located in the buffer, and 0, otherwise).	Major Metro and train stations / Proximity of 1400 meters
Angular Integration 3km	Calculated in DepthmapX using space syntax theory, GIS intersected speed with street network, continuous variable	Degree of integration of each street segment
Topological Choice R3	DepthmapX using space syntax theory, GIS intersected speed with street network, continuous variable	Street segments / Degree of choice
Connectivity	DepthmapX using space syntax theory, GIS intersected speed with street network, continuous variable	Street segments / Degree of connectivity

Asphalt	GIS intersected Asphalt with street network, finally export into final data set, dummy variable (values of 1 if segment is located in the buffer, and 0, otherwise)..	Road surface type of asphalt for the street segment
Stone tiles	GIS intersected stone tiles with street network, finally export into final data set, dummy variable (values of 1 if segment is located in the buffer, and 0, otherwise).	Road surface type of large stone tiles
Interlocking	GIS intersected interlocking with street network, finally export into final data set, dummy variable (values of 1 if segment is located in the buffer, and 0, otherwise).	Commonly made from cement or concrete, and tend to simulate the effects of cobblestone pathways
Gravel	GIS intersected gravel with street network, finally export into final data set, dummy variable (values of 1 if segment is located in the buffer, and 0, otherwise).	Road surface type of made of tiny stones
Unpaved	GIS intersected unpaved with street network, finally export into final data set, dummy variable (values of 1 if segment is located in the buffer, and 0, otherwise).	Road surface type of dirt paths
Bike lanes	GIS intersected bike lane with street network, finally export into final data set, dummy variable (values of 1 if segment is located in the buffer, and 0, otherwise).	Street segments / Bicycle infrastructure type (separated with a small curb)
Bikeways	GIS intersected bikeways with street network, finally export into final data set, dummy variable (values of 1 if segment is located in the buffer, and 0, otherwise).	Street segments / Bicycle infrastructure type (separated with over a meter buffer from the road)
Allowed to bike in the opposite direction	GIS intersected opposite direction with street network, finally export into final data set, dummy variable (values of 1 if segment is located in the buffer, and 0, otherwise).	Street segments / Bicycle infrastructure type (cyclists allowed to cycle in opposite direction in a one way street)
Painted lanes	GIS intersected painted with street network, finally export into final data set, dummy variable (values of 1 if segment is located in the buffer, and 0, otherwise).	Street segments / Bicycle infrastructure type (bicycle path in the road only has a painted line to separated the to modes)
Population Density	GIS intersected population with street network, finally export into final data set, continuous variable	Number of people per km squared / degree of density
Business location Density	GIS intersected business location density with street network, finally	Business location per km squared

	export into final data set, continuous variable	/ degree of density
Residential-commercial Residential-recreational Residential-recreational-commercial	GIS intersected three land use combinations with street network, finally export into final data set, Dummy variable (values of 1 if segment is located in the buffer, and 0, otherwise).	Land use per neighbourhood / land use class

3.3 Data Analysis

GIS reveals more profound insights into data, such as patterns, relationships, and circumstances. It analyzes the spatial environment and organizes layers of information into visualizations using maps and computable file formats for statistical analysis. The GIS process was used to perform spatial and geographical operations, join datasets, compute and perform analysis that secondary data can not provide, creating the proximities from the amenities location and then joining to street segments; the process is illustrated in Table 1 above. Space syntax is used for specific measures that correlate with human spatial behaviour to forecast and analyze the effects of urban space on users. Space syntax has been used in this study to identify the high and low levels of connectivity, integration, and choice levels in the network. These results create the basis for comparing urban form factors.

3.4 Space Syntax

DepthmapX

Data analysis for street integration, topological choice and levels of connectivity both occur in DepthmapX, a program that analyzes street networks. This data analysis, processed here, also provides data input for the OLS regression model analysis and is prepared before the OLS analysis. The beginning process to analyze the data in DepthmapX, data is processed into axial maps. Axial lines are the most extended visibility lines in urban contexts, representing unique linear spaces. An axial line map is computed to check if all street segments are linked; having them linked is crucial for the ability of the analyses to be performed. After the axial map is processed, DepthmapX is used to create a segment map further to examine all the Rotterdam's street network segments. Once this is presented, further analysis can occur. Connectivity of the network was processed next; connectivity highlighted how connected each street segment is with the rest of the network, from blue being least connected to red being most connected. Once the axial map, segment map, and connectivity values were calculated, integration measures were used; they explain the number of street-to-street transitions required by a street segment. Angular integration measures the short path from street to street with the fewest turns through the network (Hillier, 1996; Hillier & Hanson, 1984). The analysis finds street segments called 'most integrated' and is usually represented with hotter colours, such as red or yellow. After, the topological choice was measured to highlight the most effortless path, which can be viewed as how water flows or, for this purpose, the easiest path in the street network (Hillier, 1996; Hillier & Hanson, 1984). Angular integration and topological choice were processed, but metric integration was not, as the literature states. It does not show significant enough results to influence bicycle usage (Rybarczyk & Wu, 2014; Turner, 2007). Angular integration and topological choice, the global network and a local distance of radii 3 kilometres for angular and topological choice were processed; these were chosen based on the literature (Hillier & Iida, 2005; Yamu et al., 2021). In addition to the radius 3 for topological choice was chosen based on the literature, it is defined by a fixed topological depth from an origin (e.g. three directional changes) (Hillier & Iida, 2005; Sharmin & Kamruzzaman, 2018). For instance, in radius 3, only three turns are counted departing from each street segment, where for global, it would be for the whole network and is often referred to as jargon (Hillier & Iida, 2005; Yamu et al., 2021). However, only the local radius/radii (topological distance of 3 and angular distance of 3 kilometres) was used later in the final model as the global network showed no significant effect in regression models. GIS has later been used to combine these results with geographic data mentioned above to be later able to export the Geodata into a delimited text file for the statistical analysis. Angular integration and topological choice serve as the components of the second primary independent vector variable. At the same time, connectivity was added to the control variables as the literature mentions it does not directly affect bicycle movement but should still be controlled (Pafka et al., 2020).

The results from the GIS processes are aggregated and analyzed in statistical software; the data has been tested for multicollinearity between one another to identify if one or many variables would explain the other. In order to test for possible multicollinearity, which would bias the regression estimation, the correlation between the explanatory variables has been estimated. With correlations all lower than 0.3, there is no concern about multicollinearity. After testing for multicollinearity, an OLS regression was performed to examine for a possible significant correlation between the dependent variable (number of bicycle usage) and the independent variables. The intention of using regression analysis is to answer the more significant question: Do streets with high network choice and integration with several bicycle infrastructure design elements lead to a higher number of bicycle users?

3.5 Choice of Empirical Model

The literature informed the choice to use Ordinary Least Squares regression (OLS) as many studies analyzing the impacts of the built environment on bicycle usage chose the same regression analysis

Faghih-Imani et al. (2014) McCahill & Garrick, (2008) Pan et al. (2009) Raford et al. (2007), Rybarczyk & Wu, (2014), Saelens et al. (2003), Vandenbulcke et al. (2011). The literature stated two other popular regression models when analyzing impacts on bicycle usage, Multi-Nominal and Spatial lag (Cui et al., 2014; Gao et al., 2018; Koohsari et al., 2020; Zhao et al., 2020). The multi-nominal model predicts categorical variable placement in or the probability of category membership on a dependent variable based on multiple independent variables. In comparison, Spatial lag uses raw Geodata (spatial attributes latitude and longitude) in the model to understand spatial heterogeneity. The spatial lag model was not appropriate as the data for this study also has spatial attributes and needs to be coded in GIS; this study did not look to understand the spatial heterogeneity.

OLS offers the analysis of the data based on its assumptions that it is linear in parameters, has a random sampling of observations, error terms should be normally distributed, and observations of the error term are uncorrelated with each other, which the final model chosen holds (Neter et al., 2004). As the number of bicycles on a given street is a continuous variable and only one time period is considered, the standard OLS regression is deemed to be an appropriate method to examine the influence of various built environments and geographical factors. An OLS regression offers a part of the answer to the main research question: Do streets with high network choice and integration with several bicycle infrastructure design elements lead to a higher number of bicycle users? Through regression analysis, the effect of multiple built environment components on bicycle usage can be calculated simultaneously while isolating which specific factors have significant influences. These additional results provide answers to the secondary research questions mentioned in the Introduction.

3.6 Ordinary Least Squares regression (OLS) Model

A few different variations are conducted once the OLS was chosen as the appropriate statistical model to use in this study. First, a model with all the main independent variables is analyzed; this included the vectors of the street network and bicycle Design variables; this model showed interesting results but had a low R squared, as there were no control variables. Second, a model with the main independent and the control variables this model still showed a low R squared. To improve the R squared and to delve deeper for answers, interactions between variables were created; a variety of different combinations were devised; however, in the end, nine were kept, which can be found in Table 3. Nine interactions were kept as the other combinations did not show enough impact on bicycle usage, and there was no significance from their interaction in the model.

Being aware of the limitations of the OLS model, only interpretation about significant correlation and not causal interpretation can be made and are described in Chapter 4.The structural form of the model is given by following regression equation 1:

$$\textbf{(1)}\ \log Bike\ Usage_i = \beta_0 + \beta_1 Streetnetwork_i + \beta_2 Bicycle\ Design_i + \beta_3 \gamma_i + \beta_4 \theta_i + \varepsilon_i$$

where is log Bike Usage$_i$ the logarithmic term for the dependent variable, for each street segment i. The first independent variable Streetnetwork$_i$ which is a vector variable consisting of angular integration and topological choice are continuous variables. Integration variable representing the level of angular integration and topological choice i of each street segment is based on space syntax theories.

The second independent variable Bicycle Design$_i$ is a vector containing several variables describing good bicycle design as taken from the literature.[1] The variables of the bicycle design vector are coded as dummy variables. A dummy variable equals 1 if in the regarding street segment, the bicycle design is present. Next, γ_i represents a vector of control variables consisting of continuous variables (Job and population density, integration with the radius of 3km) and dummy variables (combined land uses residential-commercial, residential-recreational, and residential-recreational-commercial). Lastly, θ_i represents a vector of interaction variables consisting of population density and angular integration, business location density and bikeways, speed and asphalt, residential-recreational and topological choice, residential-commercial and topological choice, residential-recreational and angular integration, residential-commercial and angular integration, speed and bike lanes, and distance to transit stop areas and bikeways). Across the dataset, the random error term, ε_i, is presumed to be normally distributed.

The error term may consist of a number of sociological components of unobserved factors like, for example, attitude towards transport modes, social order (Class) or perceptions on bicycle mode (safety, speed, sustainability, etc.

3.7 Descriptive Analysis

Table 3 depicts the summary statistics of the data set used in the OLS regression.
The dependent variable number of bicycle usage is strongly left-shifted. To smooth the variable for a normal distribution for a better fit of the OLS model, the logarithmic term of the dependent variable is used (see Figure 2).

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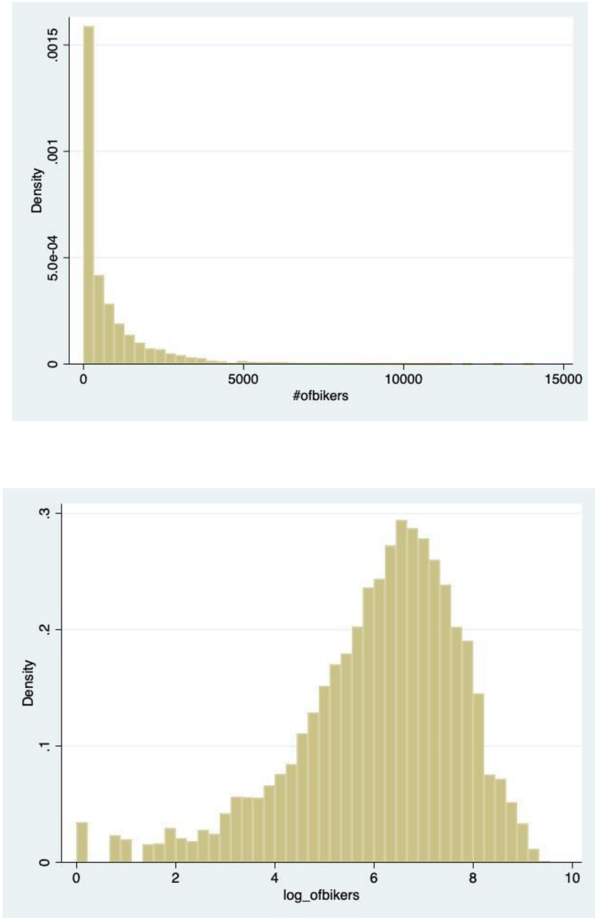
[1] Speed of the road, distance to parks, distance to transit stop areas, distance to bicycle parking, distance to major stations, types of road surface (Asphalt, stone tiles, interlocking stones, gravel, unpaved), types of bicycle infrastructure (Bikeways, Bike lane, allow to bike in the opposite direction, and painted lanes in the street).

[2] The correlation of the variables between transit stop areas and bikeways is small. The interaction term is

Figure 2 Density of the Dependent Variable



After taking the logarithm, the dependent variable has a mean of 6.065 with a range that goes from 0 to 9.55. The standard deviation of 1.68 is relatively low meaning that the data points are closer to the mean of the variable.

The topological choice variable, one of the main independents, has a mean of 9.11e+21 with a range from 7.92e+19 to 6.21e+23. The standard deviation of 3.25e+22 is very high meaning that the data points are further away from the mean of the variable and the data observations are more spread out across the range of the variable. When viewing topological values in Figure 3, the standard deviation of 3.25e+22 represents that, in general, the City of Rotterdam has a low level of topological choice but overall higher than angular integration.

The angular integration variable, one of the main independent variables, has a mean of 3.55e+15 with a range from 0 to 9.00e+15. The standard deviation of 1.23e+15 is very high meaning that the data points are further away from the mean of the variable. When viewing topological values in

Figure 4, it is clear why the standard deviation is 1.23e+15 as most of the street segments are blue or low levels of integration.

Table 2 Summary Statistics of the OLS Variables

Variable	# of Observations	Mean		Std. Dev.		Min	Max
Log of bicycle counts	20,119	6.064622		1.6796		0	9.551231
Angular integration	24,919	1.95e+15		6.02e+14		-1.00e+15	3.69e+15
Topological choice	24,923	9.11e+21		3.25e+22		7.92e+19	6.21e+23
Population Density	26,320	7675.742		5198.986		0	20927
Connectivity	24,919	3.55e+15		1.23e+15		0	9.00e+15
Business location Density	26,320	-93.92122		8110.037		-657894.8	26.55738
Speed	25,702	3.275387		1.169579		1	8
		Frequency		**Percent**			
(**Dummy**) (*Proximity to*)		**0**	**1**	**0**	**1**		
Parks	26,320	5,443	20,887	20.68	79.32	0	1
Transit stop areas	26,320	3,822	22,498	14.52	85.48	0	1
Bike parking	26,320	19,795	6,525	75.21	24.79	0	1
Transit Stations	26,320	6,161	20,159	23.41	76.59	0	1
Asphalt	26,320	16,895	9,425	64.19	35.81	0	1
Tiles	26,320	25,066	1,254	95.24	4.76	0	1
Interlocking	26,320	13,268	13,052	50.41	49.59	0	1
Gravel	26,320	26,301	12	99.93	0.07	0	1
Unpaved	26,320	26,314	6	99.98	0.02	0	1
Bike lanes	26,320	18,501	7,819	70.29	29.71	0	1
Bikeways	26,320	23,937	2,383	90.95	9.05	0	1
Opposite	26,320	26,070	250	99.04	0.96	0	1
Painted lane	26,320	25,867	453	98.28	1.72	0	1
Residential-commercial	26,320	26,066	254	99.03	0.97	0	1
Residential-recreational	26,320	18,424	7,896	70	30	0	1
Residential-recreational-commercial	26,320	18,118	8,202	68.84	31.16	0	1
(**Interactions**) Population density and integration	24,919	1.54e+19		1.20e+19		-7.89e+18	6.16e+19

Business location density and bikeways	26,320	.6148994	2.689076	0	26.55738
Speed and asphalt	25,702	1.297292	1.931609	0	8
Residential-recreational and topological choice	24,923	3.16e+21	2.22e+22	0	6.21e+23
Residential-commercial and topological choice	24,923	3.25e+19	1.47e+21	0	2.03e+23
Residential-recreational and angular integration	24,919	1.60e+13	9.09e+14	-1.00e+15	3.69e+15
Residential-commercial and angular integration	24,919	5.53e+14	1.78e+14	0	3.03e+15
Speed and bike lanes	25,702	.9841257	1.71281	0	8
Proximity to Transit stop areas and bikeways	26,320	.0789514	.269668	0	1

4. Results

In the following section, the results from the space syntax analysis, Space syntax with bicycle Infrastructure and OLS regression and maps juxtaposing space syntax and regression results will be presented. The results from space syntax analysis consist of values of connectivity, angular integration and topological choice. The OLS regression results exhibit only two of the modes run, one with only the main independent variables and the second with the control variables. The first column is conducted to see what effect the main independent variables have without controlling for other factors. In the second column, how the effect is or is not changing can be observed by controlling for several variables.

4.1 Space Syntax Results

Angular Integration

The angular integration map with a radius of three turns and a distance of 3 kilometres is shown in Figure 3 below. The areas to the West and East of the city centre are highlighted as the most spatially integrated areas of the city. The official city centre lacks high levels of integration. The second area highlighted is the Feijenoord; it is adjacent to the city centre on the other side of the river and is known for its busy cruise terminal. Street segments that tend to be longer in length and straighter appear to have high levels of integration. Areas with a denser street segment structure appear to have more street segments with high integration levels than areas with an attenuated street segment structure with low levels of angular integration. The streets of highest integration are the East Beijerlandselaan, Nieuwe Binnenweg and the west side of Dorpsweg. The streets of the lowest angular integration are Middenhagen and Jean Augierstraat.

Topological Choice

The topological choice map with a radius of three turns and a distance of 3 kilometres is shown in Figure 4 below. The city centre and the Feijenoord area are highlighted as having the most topological through movement areas of the city. Some smaller areas around the city have also been highlighted, often representing popular retail streets or strong grid structure neighbourhoods. In comparison, the least topological through movement streets are on the city's outskirts, which has long street segments that often did not connect to main streets. Areas with a denser street segment structure with short lengths appear to have more street segments with high choice levels than areas with an attenuated street segment structure with longer lengths, showing low levels of topological choice. However, it is clear from the map that Rotterdam’s street network has a high overall topological choice. The streets of the highest topological choice are the Nieuwe Binnenweg between Clases de Vrieselann and S-Gravendijkwal, Weena, which is, located right in front of the main train station in Rotterdam and Boezemstraat. The streets of the lowest topological choice are located in the northeast Chris Lebeauhof and Christa Ehrlichhof.

Connectivity

Areas with grid structures that have short street segments have the highest level of connectivity. These areas can be seen on the map of Figure 5, with Neighbourhoods like Middelland, Charlois and Hillsluis being highlighted. These neighbourhoods generally show a high number of direct connections to neighbouring streets. Areas in the dark and light blue representing low amounts of connectivity can be seen in the city's outskirts where the roads are longer, with many curves and with minimal intersections with other streets. The streets with the highest connectivity are the Nieuwe Binnenweg between Clases de Vrieselann and 'S-Gravendijkwal, Statenweg by Blijdorg metro station and Oostplein. The streets of the lowest connectivity are located in the northeast Swalm and Chris Lebeauhof.

Figure 3 Angular Integration levels of the street segments of Rotterdam

Figure 4 Topological choice levels for Rotterdam

Figure 5 Connectivity levels of street segment for Rotterdam

4.2 OLS Regression Results

In the following part, the results of the Ordinary Least Squares regression model (Table 4) are presented, discussed and interpreted to understand the different effects of urban form factors on bicycle usage in Rotterdam. First, the effect of the leading independent variables topological and bicycle design without any control variables has been estimated (Col. 1). Second, the primary regression with several control variables and interactions is performed (Col. 2).

Table 3 Results of OLS Regression

	Coefficient	T- Statistic	Coefficient	T- Statistic
Explanatory Variables	Log of Bicycle Usage		Log of Bicycle Usage	
Angular Integration R3	6.17e-17**	3.27	-4.67e-17	-1.23
Topological Choice R3	2.33e-24***	7.52	2.85e-24***	6.93
Speed of the road	0.133***	13.70	0.224***	11.57
Proximity to parks	.0547*	1.98	-0.0152	-0.55
Proximity to transit stop areas	0.597***	17.11	0.505***	13.87
Proximity to bicycle Parking	0.228***	8.84	0.216***	8.41
Proximity to major stations	0.423***	14.90	0.256***	8.71
Asphalt	0.189***	4.69	0.520***	6.33
Stone tiles	-0.307***	-4.66	-0.298***	-4.57
Interlocking	-0.611***	-14.41	-0.602***	-14.32
Gravel	-0.990*	-2.11	-0.753	-1.60
Unpaved	-1.677	-1.60	-1.396	-1.35
Bike lanes	0.402***	14.86	0.645***	8.96
Bikeways	0.707***	18.75	0.678***	7.11
Allowed to bike in the opposite direction	0.466***	4.37	0.331**	3.14
Painted lanes in the street	0.398***	5.17	0.302***	3.96
Connectivity			-1.72e-17	-0.42

Population Density			0.0000202*	2.57
Business Location Density			0.00000519***	3.98
Residential-commercial			0.505	1.26
Residential-recreational			0.423	1.90
Residential-recreational-commercial			-0.512*	-2.41
Interaction Terms:				
Population density and angular integration			1.01e-20	2.79
Business location density and bikeways			0.0415**	7.35
Speed and asphalt			-0.0828***	-3.87
Residential-recreational and topological choice			-9.84e-25	-1.60
Residential-commercial and topological choice			7.22e-24	1.08
Residential-recreational and angular integration			3.27e-17	0.81
Residential-commercial and angular integration			2.33e-16	1.20
Speed and bike lanes			-0.0644**	-3.20
Proximity to transit stop areas and bikeways			-0.275**	-2.63
Constant	4.566***	61.76	4.397***	37.73
Number of observations	19,003		19,003	
R-squared	0.1825		0.2047	
Adjusted R-squared	0.1818		0.2034	
	* p<0.05, ** p<0.01, *** p<0.001			

Integration values radius of 3 for Angular/Topological Choice

When angular integration has a one unit increase, the number of bike usage increases by 6.17e-15 bikes. The effect is approximately zero, but the result is significant (see col. 1, Table 4). As hypothesized, there is a low correlation between angular integration and bicycle usage; thus, high levels of angular integration on street segments encourage users to a minimal effect. In the second column, when the control variables and interaction terms are added, the effect of angular integration on the dependent variable decreases becomes negative and is not significant anymore. The change in the value and significance level of the coefficient when adding the control variables indicates that the control variables explain a significant part of the effect of angular integration in the first column. These results contradict what is stated in the literature; it is mentioned that angular integration displays a positive correlation with the impact of bicycle usage (Raford et al., 2007). The reason for this low impact is that angular integration might place too much or too little importance on street structures that are overly curved or pose strong right angles. Analysis of angular integration might fail to analyze the nuances of bicycle travel behaviour and might need further research.

At the same time, if the topological choice is increasing to one higher degree, the number of bike usage increases by 2.33e-22 bikes. The effect is almost zero but highly significant (see col. 1, Table1). As expected, there is a positive correlation between topological choice and bicycle usage; thus, street segments with increasing topological choice encourage users. As stated in the literature, individuals naturally choose paths with better network choice (Hillier & Iida, 2005; Sharmin & Kamruzzaman, 2018). Adding several control variables and interaction terms in the second column only changes the coefficient of topological choice minimally, and it remains highly significant. These results help answer the research question: Is there an interaction between integration, choice and bicycle infrastructure design that would lead to an exceptional amount of bicycle usage? Although the impact on bicycle usage is minimal, it is significant to present that bicycle infrastructure should be located on street segments with high topological choice. In the hopes of investigating the results, the literature mentions that the level of choice on street segments should be high in order to impact through movement (Sharmin & Kamruzzaman, 2018). Overall, for the case of Rotterdam, the level of topological choice is low, as seen in Figure 4. Perhaps if Rotterdam improved its street network structure with a focus on improving topological choice, the results would show a higher impact on bicycle usage.

Bicycle Design containing vectors

In general, when components of bicycle design are increasing, so do the number of bicycle counts. Accounting for all variables and interaction terms of the regression, the following correlation between the bicycle designs and the dependent variable can be found in the second column: If bikeways are present, the bicycle count increases significantly by 67% bikes in a given street segment in comparison to those that do not have bikeways. Significantly, if the proximity to transit stop areas is within a radius of 800 meters, the number of bikes in the street segment increases by 50% more than those not in proximity. These two results highlight the leading factors, which should be implemented when trying to encourage bicycle usage.

The following bicycle infrastructure designs, *allowing cycling in the opposite direction* (33%), *bike lanes* (64%), and *proximity to major stations* (25%) have a significant positive impact on the number of bikes in a given street segment (the coefficient of the explanatory variables is stated in the parentheses and can be found in the second column of Table 4). These results directly answer the research question: What combination of bicycle infrastructure design elements results in the most bicycle usage? The above mentioned bicycle infrastructure design factors have the highest impacts. Other interesting results are *painted lanes in the street*, which increases the number of bicycle counts by 30%, and *proximity to bicycle parking* which has a significant positive effect of 21% more bikes in a street segment. The results show that having robust and safe bicycle infrastructure has a strong relationship. Moreover, it is important to add good design details as proximity to public transit stations and stops also shows favourable conditions. The outcomes presented show that the higher the amount of bicycle design elements, the more impact it will have on bicycle usage. The above-mentioned results are in line with the literature; for example, bikeways and close proximity with public transit are said to provide the most level of design for their functionality, safety, and ease of use (van Govererden et al., 2015; Hull, 2004; Pasha et al., 2016; Zhao et al., 2020). These results are closely aligned with the literature and confirmed the research hypotheses (Forsyth & Krizek, 2011; Hull & O'Holleran, 2014; Krizek & Roland, 2005; McNeil et al., 2015; Liu et al., 2017; Saelens et al., 2003).

Conversely, the results show that factors that do not encourage bicycle usage have a negative or shallow effect; for example, different kinds of road types: Stone tiles and interlocking have the most substantial negative impact on the number of bikes on the road. Road types like gravel and unpaved negatively impact bike usage but not significantly (Col. 2). These results make logical sense, as cyclists prefer riding on smooth surfaces rather than rough or bumpy ones; this can be due to safety, comfort, and protection of cargo (e.g. material goods, groceries, plants, furniture, etc.). In the end, surfaces that are not smooth provide risks for the cyclists to injure themselves, and cyclists prefer safe, smooth bicycle routes (Harms & Kansen, 2018; van Goeverden et al., 2015).

One interesting result that literature stated to have different results from this study is the correlation between proximity to parks and the number of bikes (Fraser & Lock, 2011). The correlation is small with a relatively small coefficient of 5.74 compared to the other bicycle design variables and is only weakly significant in the first column and turns insignificant and negative when adding several control variables. This result might be an outcome of adding patterns of urbanization components to the model as they are control variables. The results of the control variables highlight that parks might not attract as many cyclists as previously thought. This might explain nuances like parks correlated with density. This should be further analyzed in future studies. These results will be mapped in order to further analyze and interpret in the discussion section.

Interactions between Variables

A few interesting results occur when the regression accounts for interaction between variables. When speed increases in a street segment that has asphalt as its road surface, the number of bike usage decreases significantly by -8.28 bikes. This decrease can generally be explained by the fact that roads with faster speeds see smaller numbers of bicycles; for example, highways or roads with 80km speed do not have cyclists on them. This explanation may also justify the interaction results with speed, and bike lanes as the test show a negative relationship with a coefficient of -6.44. The literature coincides with these results stating that cyclists prefer roads or paths with low speed, as a cyclist speed is much lower than a vehicle; thus, these lower speeds produce a safer environment (Deliali et al., 2020; van Govererden; Hull, 2004; McNeil et al., 2015; Zhao et al., 2020). However, this result could also be explained as roads with faster speed limits with separated bikes still do not make the user feel safe or that these roads with faster speeds, in general, do not offer other factors to encourage cyclists (e.g. lack of amenities, geographical compositions). However, causal interpretation cannot be made based on this research, and further investigation is necessary.

Next, when a street segment is close to a transit stop area and the bicycle roads are present, there is a significant decrease in bicycle usage, which contradicts the literature. Other types of bicycle infrastructure might explain this and might have a more positive effect than bikeways when in proximity to transit stop areas. Another explanation could be that the transit stop areas are very close to homes, and individuals walk to these transit stop areas.[2] Lastly, when there is an interaction between business location density and bikeways, there is a significant increase in bicycle usage; this coincides with what is found in the literature with these factors (Ewing & Cervero, 2010; Xia et al., 2020). This result can also show that bikeway networks in high job density locations can lead to more bicycle usage. This interaction term answers one of the secondary research questions: How significant is the impact of patterns of urbanization on bicycle usage? Thus, the results highlight that patterns of urbanization do significantly impact bicycle usage and should be considered when trying to encourage bicycle usage.

4.3 **Mapping Results**

Based on the results from the OLS, a variety of factors show a high impact on bicycle usage. In order to understand what this looks like and where it is located in Rotterdam, six maps are

[2] The correlation of the variables between transit stop areas and bikeways is small. The interaction term is more strongly correlated with bikeways, which means that the dummy of bikeways might more substantially explain the significant effect of the interaction term. However, as the interaction term has a significant negative effect and both dummies are significant and have a larger impact, it is relevant to discuss the interaction term.

juxtaposed. Maps were created to visually aid the results from the regression test to show nuances of relevant aspects of the existing physical network to assist the reader. The variables in the maps below used are transit stop areas, major transit stations, bicycle parking, parks, level of angular integration, topological choice and connectivity and the number of bicycles. Figure 8 highlights bicycle amenities, transit stop areas, major transit stations, bicycle parking, and parks with the number of cyclists to highlight patterns of cyclists. Two maps were created, one with just bikeways Figure 6, and the other with just the number of cyclists Figure 7, to analyze cyclists' movements. Lastly, three maps juxtapose bikeways with the three space syntax measured for this study (angular integration Figure 9, topological choice Figure 10 and connectivity Figure 11). This juxtaposition was created to visually examine the relationship bicycle infrastructure design has with space syntax theories in answering secondary research questions. In the maps below, bikeways are shown in dark brown. The level of angular integration, topological choice and connectivity are represented from low to light blue, medium green, and high in red.

4.4 **Built Environment with Bicycle Counts**

Bikeways

In Figure 6 (Map 1), bikeways are isolated to view the pattern of the cyclist infrastructure; there is a vast network moving in different directions. Most routes follow major automobile streets and become denser in the city's centre and across the river to the south, which is the second hub of the city. Generally, the network of bikeways looks complete; however, it is essential to note that many segments are disconnected from the network or gaps within the network. These gap and disconnected segments tend to be in the outskirts of the city's to the North, East and South from the city centre. For the size of Rotterdam, it is interesting to highlight that aside from the ferries; there are only four bridges to cross the river Nieuwe Mass by bicycle; the bridges represent the only connection between the north and south parts of the city.

Number of cyclists

In Figure 7 (Map 2), the amount of bicycle usage is isolated to analyze the patterns of cyclists' movements in the City of Rotterdam. From the map, it is clear that cyclists use a web of streets to reach the city centre. The segment containing the most red represents the highest number of cyclists is the street Weena Figure A1 that runs east to west and part of the road with a giant roundabout in the middle of the city. Weena seems to be a vital east-west link for the city. When further examining the centre of the cyclists' web Figure A3&4, which seems to be Rotterdam's central train station, another red axis appears, one that travels north to south through the city centre. This axis is located on the streets of Schiekade north of Weena, Coolsingel Figure A2, Schiedamsedijk Figure A5 south of Weena and Masshaven Oostzijde Figure A6 and Pretorialaan Figure A7 on the other side of the river. This north-south axis appears to be vital, connecting both parts of the city. There are two red squares in the city centre, which seem to act as a ring road for cyclists to quickly move about the city rather than traverse through the core. As mentioned in the previous examination above, only four bridges connect the north and south of Rotterdam; each bridge shows a high number of cyclists, about 5000 on each one. Away from the city centre, long straight paths leading to the city centre are highlighted in red. Lastly, interesting to note that a second north-south east-west axis appears in the Northeast area of Rotterdam. This area is known as Prins Alexander and is an inner-city suburb of Rotterdam that is isolated from the city by the ring highway around Rotterdam.

Juxtaposition Bikeways with Number of Cyclists

When comparing Figure 6 (Map 1: Bikeways) and Figure 7 (Map 2: Number of cyclists), it is shown that there are areas with bikeways, which have a low amount of cyclists, these areas are in the outskirts of the city in the north and south. These areas are poorly connected to the rest of the bicycle network and show a small road network pattern overall. However, interestingly, segments within the city have broken segments of bikeways infrastructure but still, show high bicycle users. This observation might be the product of the urban form, as it might be the only route that connects different parts of the city or is simply the quickest route available at the moment or that the more citizens live in the city centre. Furthermore, comparing the maps shows that there are many areas in the city with no bikeways, but they highlight a high bicycle usage. This might be due to two factors; the first one is that the type of bicycle infrastructure might not be bikeways but a different, less favorable form of infrastructure. The second factor is that bicycle users may be drawn to these areas because of the amenities located by these streets. Therefore, to further examine if there is a relationship between the location of amenities and bicycle usage, a third map was created with amenity variables that showed a high impact on bicycle usage from the OLS analysis.

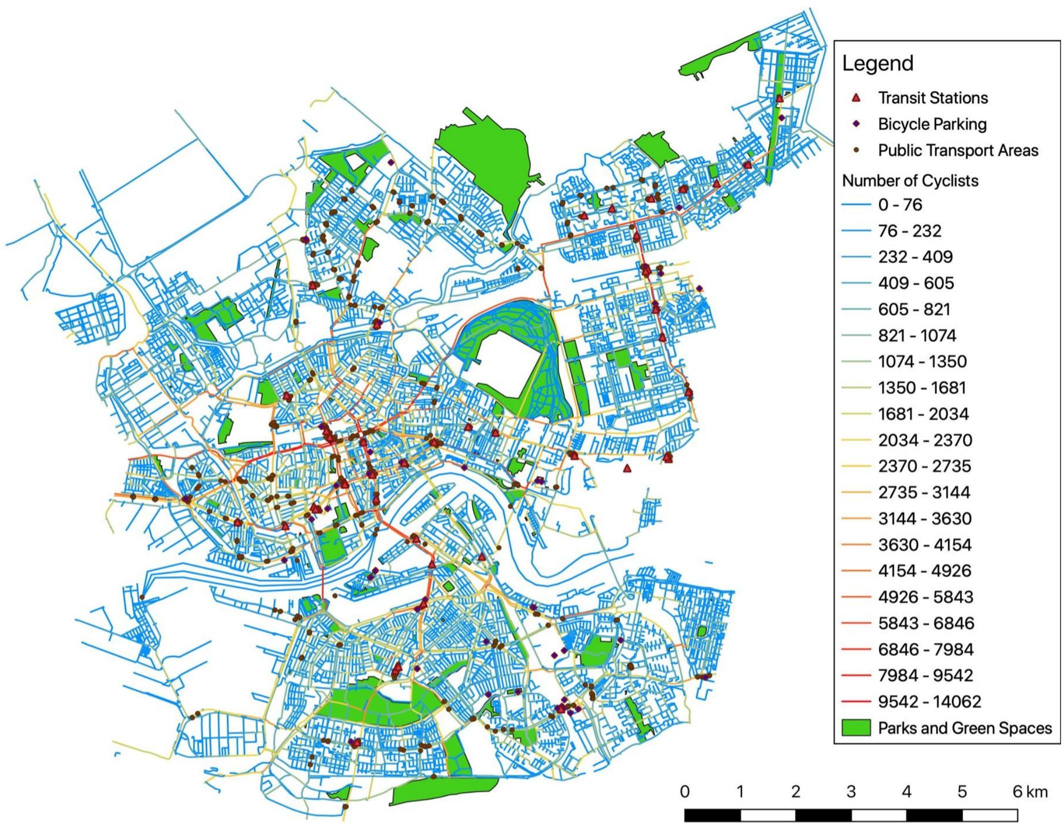
Juxtaposition Bicycle amenities *with the Number of Cyclists*

When examining if there is a relationship between the location of amenities and bicycle usage, Figure 8 (Map 3) shows that with a high density of bicycle amenities, the redder street segments become. Visually the highest impact on bicycle numbers seems to be major transit stations and transit stop areas. The increase in bicycle usage around transit locations displays that individuals integrate both modes of transport into their commutes. When examining bicycle parking, it appears to also have a visual effect on the map, as street segments become light orange as they approach a bicycle parking location. Finally, when viewing parks on the map, small parks seem to have a low impact on bicycle usage, whereas larger parks with paths going through them have a medium to a high level of bicycle usage. This observation may explain the low numbers in the OLS analysis and aligns with the literature on bicycle usage and green spaces (Pan et al., 2009). Overall the map highlights that even in more remote or on the city's outskirts, a cluster of bicycle amenities has a high number of bicycle usage.

Figure 6 Map 1 Bikeways

Figure 7 Map 2 Number of cyclists

Figure 8 Map 3 Juxtaposing Bicycle Amenities with the Number of Cyclists



4.5 Bicycle infrastructure with Space Syntax

Bikeways Juxtaposition with Angular Integration

In Figure 9 (Map 4), bikeways are on major streets acting as thoroughfares throughout the city, getting cyclists around quickly to different areas; a few of these routes are on top of the street with highly angular integration. Nevertheless, most of these routes are on street segments with low angular integration, often leaving many areas with glowing yellow-red segments. Examining the map, it is clear that bikeways are missing in central areas that could be added in the south below the river and to the west of the city centre. The composition may explain these results on the street network. Many districts have a different street pattern that does not link with one another well or in which the bikeways were an afterthought and just placed on major automobile routes.

Bikeways Juxtaposition with Topological Choice

Examining Figure 10 (Map 5), bikeways still sit on major streets acting as thoroughfares throughout the city. Only a few bikeways align with high topological choice. However, many bikeways do connect or intersect with highlighted high topological choice segments. These connections can offer individuals on the bicycle quick access to the main bicycle network of Rotterdam. There are a few pockets within the city to the south of the city centre that show high levels of topological choice; this may result from the street patterns in their respective areas. The highlighted red areas often show grid-like patterns that are tight short street segments. This type of street pattern offers a greater capacity for making turns more effortless and dramatically reduces the need for complicated, multiphase traffic signals (Gehl, 2010; Marshall, 2005).

Bikeways Juxtaposition with Connectivity

In Figure 11 (Map 6), bikeways and connectivity are juxtaposed. Gird-like areas showing orthogonal, rectilinear shapes with street connections going in multiple directions offer the highest connectivity levels. These findings from the juxtaposed map are directly in line with Marshall's (2005) findings on connectivity. These areas can be found in the city centre and west of it, areas in the south and on the outskirts where neighbourhoods have strong grid-like street patterns. Interesting to note is that areas in the south in the neighbourhoods like Charlois, Millinxbuurt, and Feijenoord show high levels of connectivity but lack bikeways within them. The bikeways in these neighbourhoods seem to run through them rather than connecting them.

Figure 9 Map 4 Bikeways Juxtaposed with Angular Integration

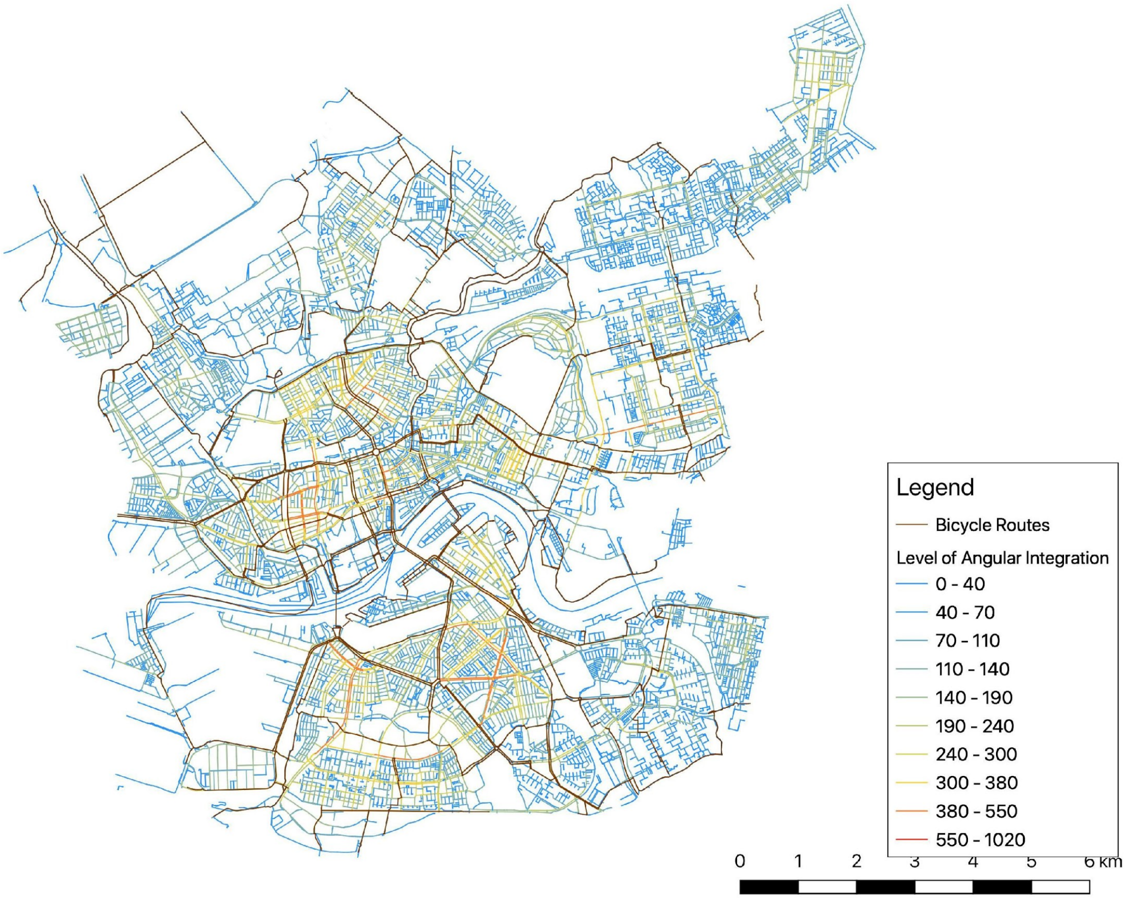


Figure 10 Map 5 Bikeways Juxtaposed with Topological Choice

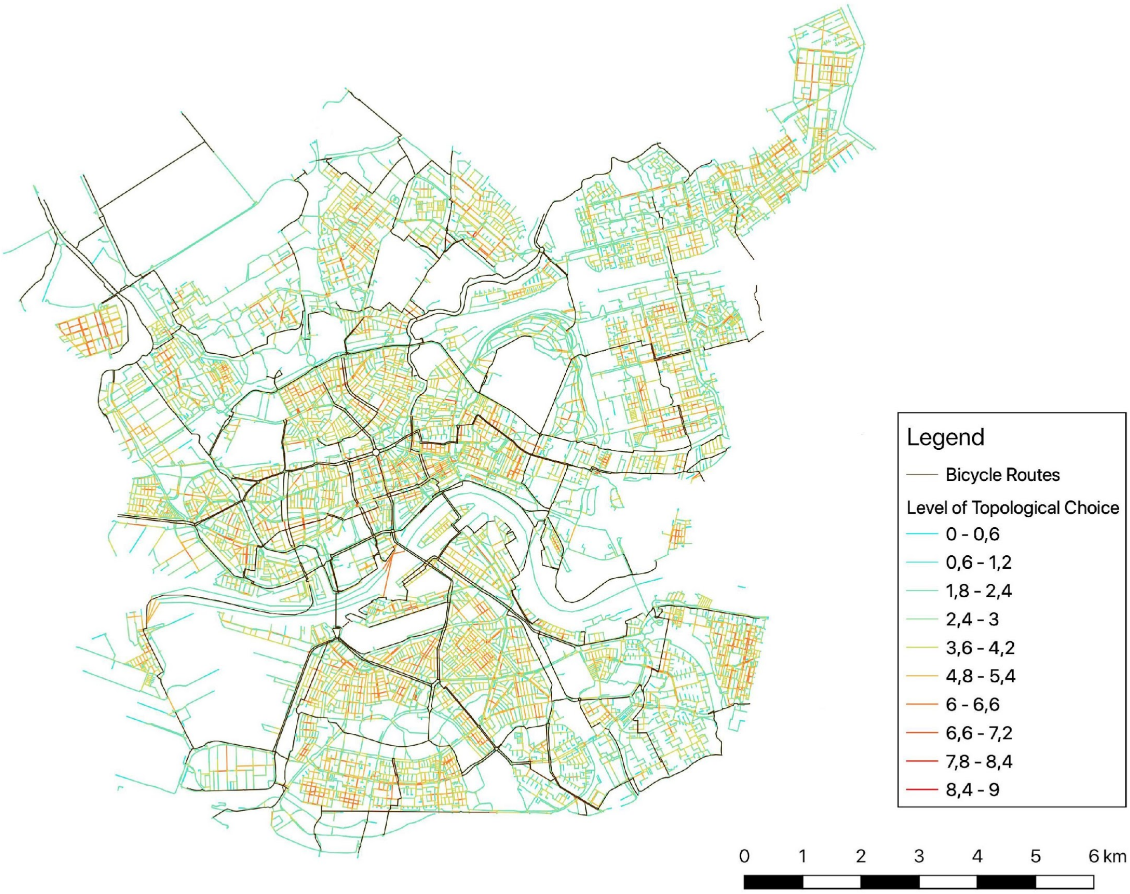
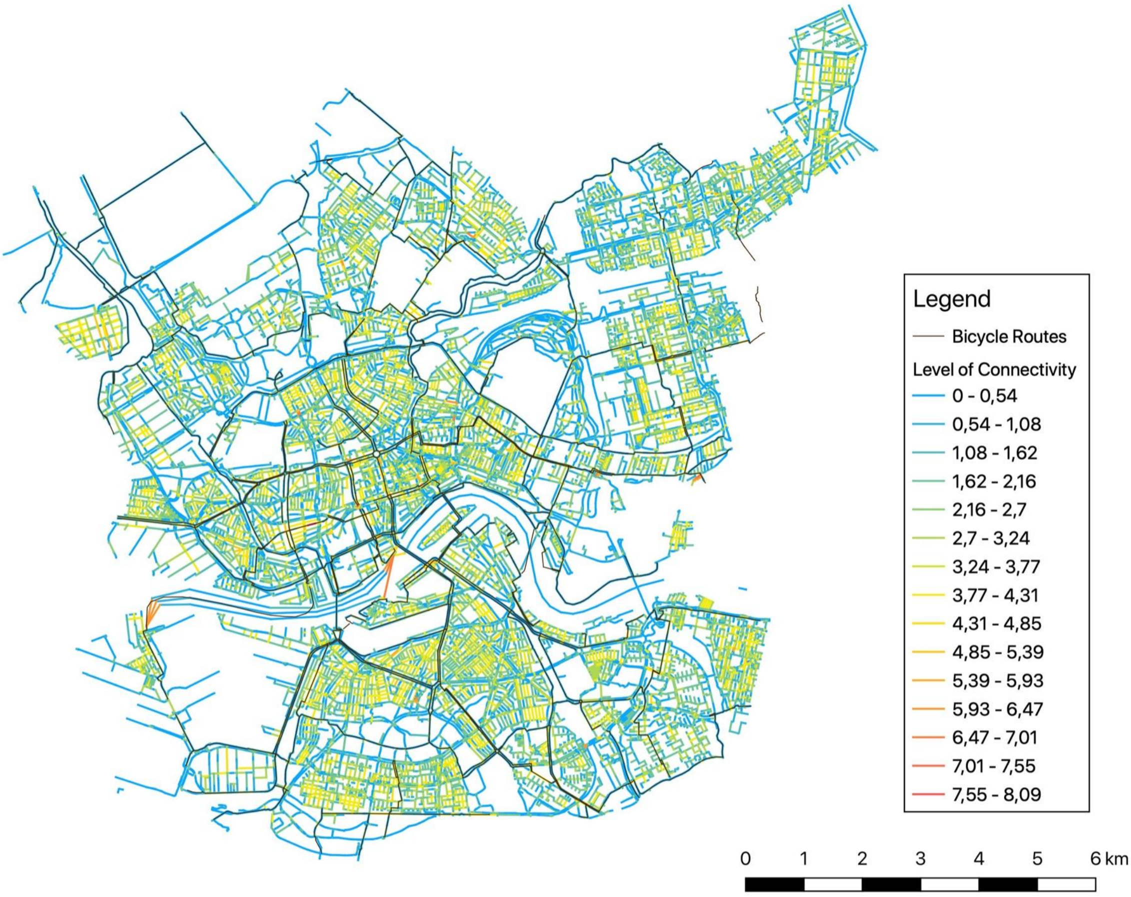


Figure 11 Map 6 Bikeways Juxtaposed with Connectivity



5. Discussion

This section aims to interpret and discuss the importance of the findings in light of what was previously known about the research problems under investigation and explain new understanding gained after considering the findings to answer the research questions of this study. This section will be organized into four parts: space syntax analysis and its juxtaposition with bikeways, the visual juxtaposition of analyses, and the contribution to planning theory ending with the limitations of this study and its methodology.

5.1 Interpretations of Space Syntax Analysis

This section will interpret all six space syntax maps with their respective spatial analysis. This was done to reduce redundancies, as the space syntax maps on their own do not need different interpretations as they are already juxtaposed with bikeways.

Angular Integration

When deciphering the angular integration results, a few exciting things happen within the city's network. There are two areas of highly angular integration beside the city centre rather than in the centre of the city Figure 3; literature mentions that the opposite should occur (Raford et al., 2007; Turner, 2007). The areas to the West and East of the city centre displayed the most integrated area of the city. These results are interesting as it is expected that central areas of a city should be higher in angular integration but are not. A reason for this may be that as the city grew in size, the street network did as well, and with that, their values of angular integration as new streets were added into the street network. This area around the centre becomes more integrated than the one in the centre because city centres rarely change as they have historical and social value. Another reason for these results might include the history of Rotterdam. It was restored from the Second World War. Rather than the city being slowly rebuilt naturally through flows of incremental growth, the streets were planned artificially, resulting in a city with inconsistencies in its angular integration. Turner (2007) explains that angular integration does not correlate with actual movement patterns but highlights the central areas to analyze further. Thus, examining Figure 9 (bikeways and angular integration), it is clear that bikeways are missing in central areas, which could be developed in the south below the river and west of the city centre. The angular measures should be used here as the future indicator of potential central areas of the system. When looking at the hypothesis' predictions, straight street segments tend to have high levels of angular integration. When curved streets are present, the amount of angular integration tends to have a low level. However, this is not the case everywhere in the network. This is because specific segments that are curved in areas with a high density of street segments allow many segments to be connected to them. These few segments compensate with their curved segments by having many connections, establishing a better level of angular integration. The overall result aligns with what was discussed in the literature about angular integration (Hillier et al., 1993).

Topological Choice

In Figure 5, topological choice presence is different from angular integration, showing many areas within the city with yellow-orange segments. Figure 5 highlights the results for the OLS analysis that this choice value produces a small but more significant effect than angular integration, which is seen in the higher amounts of yellow-orange segments. These areas appear to represent small hubs within neighbourhoods around the city of Rotterdam. However, these areas also seem to highlight dense neighbourhoods; the street structure of these hubs tends to have a composition of very short length, angular street segments that comprise many connections. Hillier & Iida (2005) mention that these hubs around the city are precisely the result of topological choice with a radius of three. According to Yamu et al. (2021), the result from the radius of three shows the highest through-movement potentials locally; thus, these highlighted areas show the potential streets on which should be linked to the city network. Lastly, there are only a few street segments with a high red level of choice; these segments are unexpected but may serve as prime streets in a neighbourhood, providing optimal movement in the area. In contrast, the segments leading to these outlying high red segments fail to do the same, highlighting a need to improve the entire network. When examining Figure 10, many areas highlighted in red represent high through movement streets but do not have bikeways, which might explain Rotterdam's low impact of choice. Thus, the juxtaposition of bikeways and topological choice highlights that further development of bicycle infrastructure in areas of high topological choice can boost bicycle usage, as indicated by the OLS analysis results.

Connectivity

High connectivity areas represent streets with many connections with other streets (Hillier & Hanson, 1984). In contrast, lots of blue in streets with few connections in areas with low connectivity, resulting in a low connectivity value (Hillier & Hanson, 1984). To further understand how connectivity works, examining areas on the map with a short street segment in a grid-like or hexagonal-like (Feijenoord neighbourhood) structure shows the highest level of connectivity. Straight streets with many nodes (intersections) offer an excellent level of connectivity, as they produce several connections to the whole street network. A consequence of poor connectivity is missing links in a network, putting an enormous strain on the connected network. These missing links create congestion and many areas for collisions to occur as a result. Connectivity is deemed essential for a functional bicycle network (Lowry & Loh, 2017). It supports bicycle transportation in a few ways. It improves destination potential, the physical network structure, continuity of bikeways, and the ability to travel farther distances (Lowry & Loh, 2017). However, based on this connectivity showed a negative impact on bicycle usage. The results are insignificant, exhibiting that Lowry & Loh's (2017) claims can be valid, though the methodology or model in this study may not have supported it. When observing Figure 11, like the other space syntax measures, many streets with high connectivity do not have the bikeway-type infrastructure, which might explain the results from the regression test. However, as mentioned in chapter 2.3, connectivity does not explain movements within streets, just how connected they are, ultimately making it challenging to interpret Figure 11.

5.2 Interpretations of Visual Juxtaposition Analyses

This section will divide the outcomes from the mapping results section into two components. One part will combine the results from bikeways, the number of cyclists and their juxtaposition, and the second will only discuss the juxtaposition of bicycle amenities with the Number of Cyclists.

Bikeways, the Number of Cyclists and their Juxtaposition

When interpreting the map of bikeways, it distinctly illustrates that most routes follow major automobile streets. The placement of bikeways is often a result of an afterthought of automotive routes. Bikeways, even in the Netherlands, are built beside or as part of the automotive network. This is especially true in Rotterdam as it was rebuilt after the war when the automobile had high prominence and the built environment was designed to accommodate the automobile. It is hard to change the built environment after it was built as citizens will not always agree on the changes, and it becomes quite costly, hence this pattern of bicycle infrastructure in Rotterdam. Bikeways becoming denser in the core of a city is a common sight as there is a high population density in the cores of cities, and as it is the core of the city, it has to be able to accommodate more individuals coming into the city for work, shopping, and play (Crucitti et al., 2006). As for the gaps in the bicycle route network, there are a few reasons for this, but the prominent ones are that either the borough is not agreeing with the city's master plan, boroughs are behind on their public works projects, or the existing infrastructure on that bicycle route section has not been updated or is deemed sufficient (Hunt & Abraham, 2007; McNeil et al., 2015).

Weena, the road that runs east to west, displays a substantial number of cyclists; it acts as one of the axes for Rotterdam. Weena may have this high number of cyclists for several reasons. The most likely reason is that it has a bikeway; it runs from east to west with only one disruption (that cyclists must cycle through Kralingse Bos, Rotterdam's largest park). Lastly, the middle of the route, the center of the city, also happens to be where the central train station of Rotterdam is located. Thus this composition of the built environment is the most significant factor for the high number of bicycle usage on this bikeway. The central train station is located just to the left of the large roundabout; the second axis intersects from north to south at this roundabout. This north-south axis appears vital, connecting both parts of the city and comprising streets like Schiekade north of Weena, Coolsingel south of Weena and Masshaven Oostzijde on the other side of the river. Although this north-south axis is not straight, it does offer the most direct route from both sides of the city when crossing the river; this axis is connected to the other routes in the southern part of the city. The part of the city north of the river unequivocally has a more considerable number of cyclists. This tends to happen in cities with considerable barriers, such as the river in Rotterdam requiring large bridges to be built, often resulting in one side of the city being more dense and developed (Pasha et al., 2016). Overall is clear that the composition of the built environment impacts the usage of bicycles; this is in line with what that literature speaks to on this topic (Ewing & Cervero, 2010; Gao et al., 2018; Koohsari et al., 2020; Winters et al., 2010).

The juxtaposition between the bikeways and the number of cyclists was created to answer one of the secondary research questions. What combination of bicycle infrastructure design indicators results in the most bicycle users? Bikeways showed the highest impact on bicycle usage in the OLS analysis. As mentioned in the results, areas that do not have bikeways but a high number of bicycle counts. The map aims to examine further how this bicycle infrastructure design is characterized visually. Generally, having a high amount of bicycle infrastructure design has the most significant impact on bicycle usage; however, it does not stand alone. There still needs to be a reason for cyclists to cycle in an area, whether that be points of interest or population density. Thus it is essential to remember that just having bicycle infrastructure in an area will not alone provide high bicycle usage.

These areas with bikeways that show a low amount of bicycle usage can be explained by having a low degree of density, connectivity, no integration with amenities and no points of interest. The different built environment factors like types of infrastructure, the location of amenities, which will be discussed later and high-level integration values (see Map 3) can produce these patterns outside the bikeway infrastructure. Thus this highlights a few assumptions that can be made when trying to encourage bicycle usage. The bicycle network needs to be connected to the whole network; the network needs to reach all crucial locations (e.g. jobs, homes, leisure), it needs to be easy to navigate; this can be improved by adding or updating street integration and be integrated with amenities to make it easier and safer to use the bicycle (e.g. train stations, bicycle parking). These assumptions follow the same line of reasoning as studies from Ewing & Cervero (2010), Forsyth & Krizek (2011), Nielsen & Skov-Petersen (2018), and van Goeverden et al. (2015). The impact of amenities on bicycle usage will be further discussed in the section below.

Juxtaposition of bicycle amenities with the Number of Cyclists

The map of juxtaposing bicycle amenities with the number of cyclists was created to visually illustrate the main independent variables, demonstrating the most significant impact on bicycle usage. In the hopes of visually understanding the answers to the secondary research question of What combination of bicycle infrastructure design elements results in the most bicycle users? The elements that exhibit the most impact on bicycle usage are surface type, type of bicycle infrastructure in transit stop areas, central transportation stations (train and metro), and bicycle parking. The map juxtaposing the number of cyclists with bicycle amenities show that areas around major transit stations and transit stop areas have high bicycle counts; the argument for this is that cyclists often combine both modes of transportation (Cervero, 1996; Cui et al., 2014; van Mil et al., 2020). The bicycle allows them to travel short distances and to other modes of transportation like public transit, which can travel further distances. In the Netherlands, this mixed-mode transportation interaction is prevalent (van Mil et al., 2020). Another reason for transit hubs to attract a large number of cyclists is that often areas around transit tend to be denser and have many points of interest around them (e,g, offices, retail, recreational services, etc.). The point of interest has not been analyzed in this study. However, land use and population have been added as control variables and show an impact; population density has a much more significant impact than land use.

Bicycle parking has a minor impact compared to the two mentioned above but still shows some exciting results, that routes around bicycle parking are highlighted in lighter colours. This shows that people will cycle to good parking if available (Chen et al., 2018). However, it might not directly be linked as the points of interest may be located beside the parking or in the vicinity as parking often is (Chen et al., 2018; Pucher & Buehler, 2008; Tilahun et al., 2007). Parks were added into this interpretation, as the results are engaging when the OLS is run with just the main independent variables park for significant impact on bicycle usage. However, once the control variables were added, parks were negatively affected; this was not expected from its hypothesis.

Nonetheless, as mentioned earlier, the explanation for this could be seen on the map that areas around small parks have a low impact on bicycle usage. In contrast, larger parks with paths going through them have a medium to a high level of bicycle usage. This explanation then supports the claims by Christiansen et al. (2016), Fraser & Lock (2011), and Pan et al. (2009) study that parks impact bicycle usage positively, but further research on the size of parks is suggested.

5.3 Contribution to planning theory

This study contributes to filling the three research gaps; it highlights the different combinations of the built environment which impact bicycle usage, it provides concrete evidence that bicycle design is the most critical factor when encouraging bicycle usage, and lastly, when choosing a city for a case study, it provides more relevant results when comparing similar built environments.

This study found a few thought-provoking outcomes to contribute to planning theory: When streets with high angular integration, high topological choice and many bicycle infrastructure design elements are present it leads to higher numbers of bicycle users. Delving deeper into the outcome shows that both do boost bicycle usage; however, in this study integration and choice levels were generally low and in the model showed a low level of impact; however, this can vary due to the topology of Rotterdam. Bicycle infrastructure design shows the highest impact of bicycle usage when combined with the control variables chosen in this study. These variables significantly contribute to planning theory as studies before tend not to put as much importance on them. Now it will highlight the importance of bicycle infrastructure design when considering how to encourage bicycle usage (van Govererden et al., 2015; Hull, 2004; Hunt & Abraham, 2007; Pusher & Buehler, 2008; Pasha et al., 2016). The better the design of the bicycle infrastructure, the more significant the impact on bicycle usage; this result is an important finding as it highlights that developing a basic design for bicycle infrastructure can indeed impact bicycle usage positively; however, if there is a need to significantly impact bicycle usage positively, using infrastructure that supports the cyclist the most will have the best outcome (best-practice). These contributions provide a solid footing to develop stronger connections on the theories of what can encourage bicycle usage. These contributions have also answered the main research questions while examining these factors, as few nuances also appeared.

The proximity to parks was said to impact bicycle usage positivity (Fraser & Lock, 2011); in this study, that was not the case; however, when visually mapped, new results emerged. On the map, a park large in size, which has bicycle infrastructure running through it, shows a high number of bicycle usage while small parks and parklets had no impact. This may be because small parks are close to the home and only have small green space amenities (e.g. playgrounds for children, plants, benches or picnic tables), which may not provide enough reason for cyclists to divert their routes. Nonetheless, creating bicycle infrastructure beside or through large parks with amenities is a reliable way to encourage the number of cyclists.

Next, high levels of angular integration and topological choice might not always encourage bicycle usage; this is mentioned earlier. When angular integration and topological choice is part of the OLS regression only with the main independent variables, it shows a significant but marginal impact on bicycle usage; however, when control variables are added into the model, angular integration becomes negative with no significance and topology stays significant with no impact on bicycle usage. These results add to the planning theory that integration and choice may not significantly impact bicycle usage as previously thought, however, it might be due to the low values in the Rotterdam network. This then highlights the need to consider using integration values when analyzing bicycle usage carefully.

Further nuances that appeared during the analysis of the leading research question provide interesting contributions; these include the size of parks; integration levels might not always encourage bicycle usage; however, topological choice does significantly impact bicycle usage.

5.4 Limitations

In this section, the limitations of this study will be presented; it is done to highlight the possible issues that might have arisen when choosing the methodology of this study. The limitations include data availability, the data used was not primary data, the study only examines one year, only one city was used (external validity), the culture of the Netherlands is pro bicycle usage finishing with the limitations of the OLS.

Data availability and using secondary data

In the theoretical debates section of this thesis, a few other variables impact bicycle usage. These variables might have provided results to explain the impact on bicycle usage better. These variables include the width of cycling paths, the size, whether intersections offer protected bicycle infrastructure or not, wayfinding (signage) for cyclists, lighting on bicycle infrastructure, and social demographic data. All these factors were unable to access for the researcher for either Rotterdam or for the year 2016 and thus were not added into the study.

Using secondary data is a reality of research that has to be considered and approached thoroughly by using the best possible methodology and being entirely transparent to illustrate possible issues. The collection and use of primary data often requires a lot of time, however offers very accurate data that can be trustworthy. It also highlights nuances that might not come up using secondary data.

Examination of only one year and one city

When examining only one year of data, the limitation is presented that different years cannot be compared. It is a problem for two reasons. First, it is not possible to compare the changes; second, there might have been considerable development and renovations in the bicycle infrastructure in Rotterdam, which would make the results of this study not valid for future implications for policymakers in the future Rotterdam.

A limitation for only examining one city at a time is external validity, which illustrates that the study results cannot be generalized and applied to other cities. This can cause issues for policymakers; however, this study intentionally chose a city with different characteristics both for street structure and culture to highlight nuances for cities that do not represent the classic small density European city.

Bike Culture of the Netherlands

Rotterdam is located in the Netherlands, a country known for its strong bike culture; it is a city and country which heavily promotes and subsidizes cycling. However, it should be highlighted to what extent these results can be generalized outside the City of Rotterdam and the Country of the Netherlands. Thus, it presents a level of external validity bias when implementing the results of this study. Cities and countries in different parts of the world will have a weaker bicycle culture, perhaps making it difficult for policymakers to gain traction for these results and for citizens to switch their mode of transportation if it is well established.

OLS Limitations

The motivation for the choice of OLS has already been explained in Section 3.5. OLS regressions are especially useful to look for significant correlations. However, they also have some shortcomings because OLS regressions do not allow causal interpretations. Thus, it is impossible to interpret from the results why there is a higher number of bikes in the street segments, only that it correlates significantly with the independent variables already interpreted. In addition, two empirical concerns could, on the counterfactual, bias the results: Reverse causality and omitted variable bias (OVB).

Reverse causality means that not only does the independent variable have an influence on the dependent variable, but also the other way around. In the case of this empirical work, this means that not only street network analysis and bicycle design factors have an influence on the number of bikes, but it could also be that a higher number of bicycles leads to the implementation of better bicycle design. This could be unknown or based on individual decisions that, due to the history of particular streets, have always been used more often, and the city planning decides to improve the bicycle lanes for these streets. In order to understand the causal relationship, what influences what and which factors drive the number of bikes, data collection from bike users through survey and further analysis is needed.

Another concern is OVB, which would bias the estimated results. OLS has a strong assumption that the error term is not correlated with the explanatory variables. The error term includes unobserved factors that influence the dependent variable. If any of these unobserved factors affect the dependent and the explanatory variables, the estimated results will be biased. The more detailed a data set is, the less likely a problem from an OVB. The more detailed a data set is, the less likely a problem from an OVB. Again, data on bike users would help to control for factors such as Dutch culture, which may influence not only the number of bikes but also the choice of bicycle design factors.

6. Conclusion

The objective of this study is to identify if bicycle infrastructure design with high network choice and integration lead to a higher number of bicycle users. In addition, it is concerned with examining which urban design factors can encourage citizens to use the bicycle the most. This study conducted an experimental study design; it used space syntax, GIS and quantitative components to explore what impact there is between urban form factors and an influence on bicycle counts. Quantitatively an OLS regression test was used to highlight which factors have the most significant impacts statistically. OLS acted as a robustness test check while GIS and space syntax prepared data and finally mapped it to understand visually. The results presented that the combination of bicycle infrastructure design with high choice and integration level does impact bicycle positively, answering the primary questions of this study. It further illustrated that bicycle infrastructure design with greater functional and safety characteristics (e.g. bikeways, asphalt surface, proximity to transit stop areas and stations) has the most significant impact on bicycle usage. It adds to the literature that bicycle infrastructure design has the most significant impact in encouraging bicycle usage.

A few nuances appeared when examining which components could answer the research questions, providing a few unexpected outcomes. For example, angular integration levels showed shallow, basically zero impacts on bicycle usage, and when combined with control variables, integration and connectivity levels had a negative impact on bicycle usage. When examining angular integration levels of Rotterdam, they are generally low, and places with high levels were not expected to be high in integration values. High areas of choice and integration were found to be around the city centre rather than inside the centre. Topological choice in both models show a low impact, but, significantly, this might be due to the placement of the bicycle infrastructure. Visually, areas with many amenities integrated with bicycle infrastructure, even in the city's outskirts, show a significant impact on bicycle usage. Lastly, in the literature, Fraser & Lock (2011) and Pasha et al. (2016) mention that proximity to parks impacts bicycles; however, this study concludes that only large parks have this impact.

The generalizability of the results of this study is subject to certain limitations. For instance, Rotterdam was chosen for its spatial characteristics; the results might be hard to reproduce in other dense European cities. However, the choice of Rotterdam poses another issue, that it is in the Netherlands, and the country already has a very high number of bicycle usage because of its encouragement and subsidy into the culture, making it hard for other countries to do the same. The data was not compared with other years or cities, creating concerns of external validity. Lastly, due to a lack of data availability, a few critical urban design factors mentioned in the literature were not included, creating a basis for the factors chosen.

These findings build on past research to examine what impacts the urban form factors have on bicycle usage and contribute to this field's literature. Building high-quality bicycle infrastructure that centres around functionality and safety is a proven approach to encourage bicycle usage in urban environments. It was previously unknown that it would encourage bicycle usage in such a significant way when combining other variables like street network analysis and patterns of urbanization like land use, population and job density. Hence, this study provides transportation engineers and urban planners with valuable insights to better design and plan new developments to promote cycling as a mode of transportation.

6.1 Implications for Policy Makers

A few suggestions were proposed in the interpretations based on the research gaps and inconsistencies identified in this study. This section will further build upon what was mentioned earlier and proposes several recommendations for policymakers to encourage bicycle usage, leading to a better outcome.

The first and the most important recommendation for policymakers is to focus on the design of bicycle infrastructure. Bicycle design with high functional and safety standards provides the most significant impact on bicycle usage. It is then suggested to update or develop infrastructure which has a large separation from automobile travel. This type of infrastructure can provide adequate safety and capacity for many cyclists.

When best practice infrastructure is not possible because of space constraints and other factors, it is still recommended to build separated infrastructure but with smaller buffers between automobiles and bicycles. Where it is applicable, building bicycle lanes in the opposite direction of a one-way automobile street, as it is shown, will encourage bicycle usage. Regarding where to build bicycle infrastructure, it should be in close proximity to bicycle amenities like major transport stations, transit stop areas, and bicycle parking. In order to positively boost the impact of bicycle usage, it is also suggested that the bicycle infrastructure should be considered being built on street segments that have high values of topological choice. Furthermore, the surface type of the bicycle infrastructure should be as smooth as possible when analyzing surface types; the smoother, the better (e.g. asphalt) because the rough or bumpy surface shows a negative effect on bicycle usage. Overall, combining the elements mentioned above can promote bicycle usage in other cities with similar city composition as Rotterdam. Finally, when considering building bicycle infrastructure by green spaces or parks, it is suggested to build infrastructure through large parks.

Other elements policymakers should consider are the patterns of urbanization, particularly the densities of business locations and the level of population density present in street segments. It is suggested to build bicycle infrastructure in areas with high population density as it shows significant encouragement of bicycle usage.

6.2 Recommendations for Future Research

It is suggested that future research should continue further studies in other bicycle design and urban form factors in order to grasp a greater understanding of which factors can additionally boost the impact of bicycle usage. In this study, a few nuances on the maps appeared. The size of parks has a varying impact on bicycle usage; to concretely understand if parks impact bicycle usage and to what degree, then the park's size should be examined to test if the results in this study are accurate and can be accepted as actual knowledge. Mentioned as a limitation, the analysis of one city may be problematic; thus, to limit external validity, it would be prudent to test multiple cities with Rotterdam's characteristics to highlight similarities and differences to confirm or deny the results in this study. Next are a few variables that have not been part of this study but have been recommended in the Theoretical Debates chapter to encourage bicycle usage. The width of bicycle lanes significantly impacts bicycles; therefore, adding the width into the future study of the same calibre is recommended. Two factors that have been mentioned in this thesis but have not been thoroughly discussed are the impacts of wayfinding (signage) and lighting on bicycle infrastructure. Wayfinding is said to make the use of bicycle infrastructure much more accessible and would guide cyclists on specific routes, thus increasing the number of cyclists in a given area. Lighting acts as a safety component for bicycle infrastructure, allowing users to see the road and the area they travel in, increasing the feeling of comfort and safety which has been shown to impact bicycle usage. When analyzing the map that juxtaposed the number of cyclists and bicycle amenities it shows that areas with a considerable amount bicycle amenities have a high number of bicycle usage, however often, areas with many bicycle amenities also concede with many points of interest (e.g. retail, jobs, recreational, institutional). Therefore, it is suggested to further analyze what types of points of interest impact bicycle usage and to what level of density. Lastly, it would be interesting to add why the components in this study showed a positive impact on bicycle usage, creating a survey in Rotterdam and asking local residents why they prefer bikeways over other infrastructure and how important it is to them that bicycle infrastructure is integrated with public transport.

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Annex

Figure A1 Weena Bikeway

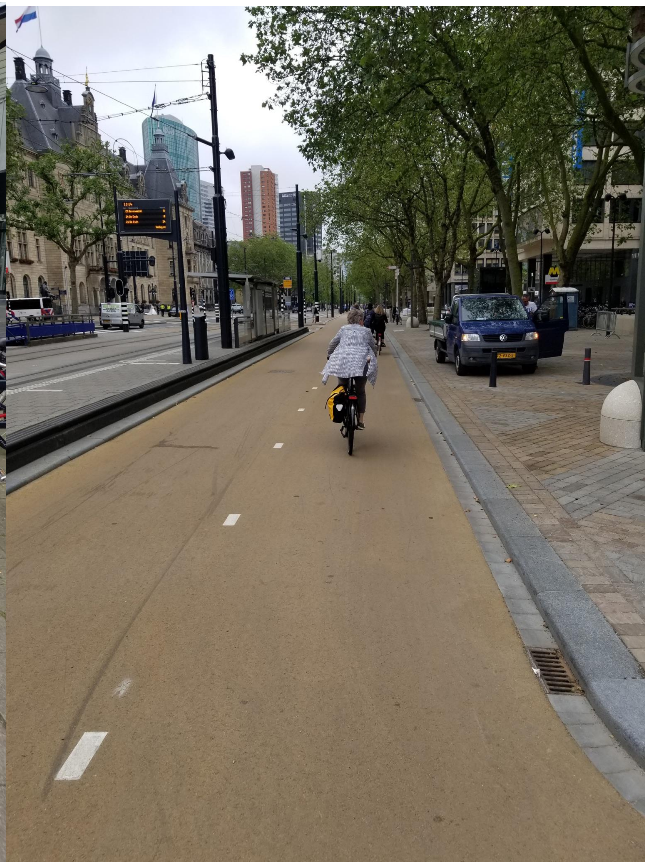

Figure A2 Coolsingel Bikeway

Figure A3 Centre Roundabout Looking North

Figure A4 Centre Roundabout Looking South

Figure A5 Schiedamsedijk Bikeway

Figure A6 Maashaven Oostzijde Bikeway

Figure A7 Pretorialaan Bikeway