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Where to improve cycling infrastructure? A case study on the city of Paris.

GEO 511 Master's Thesis

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Abstract

Cycling has become increasingly relevant in urban- and transport planning as a cheap, space-efficient, pollution-free, and healthy mode of transport. Cities around the world are aiming to increase cycling numbers by implementing sustainable mobility policies and improving cycling infrastructures. The aim of this thesis is to develop a methodology that can help in identifying potential locations for improvements of cycling infrastructures. It addresses the need for simple and effective methods to support decision-making in bicycle planning. The city of Paris is used as a case study area because the city has made considerable efforts to improve cycling infrastructures and to become more bicycle-friendly in the past years. The main data used in this project is street data from OpenStreetMap (OSM) and cycling infrastructure data from the Atelier parisien d'urbanisme (Apur). Based on a review of literature on cycling infrastructure planning and the assessment of cycling infrastructures, a method to identify where to improve cycling infrastructures was proposed. The method (1) identifies potential locations for improvements of bicycle infrastructures on a street level and (2) analyses how the potential locations change when considering accessibility to important destinations. The proposed method can be applied with commonly available data, has clear outcomes, is reproducible, and can be applied to different case study areas. The identified street segments and areas with potential for improvement of cycling infrastructures need to be further examined in the context of local policy goals.

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Abbreviations

Apur	**A**telier **p**arisien d'**ur**bansisme
DEM	**D**igital **E**levation **M**odel
DRIEA	**D**irection **R**égionale et **I**nterdépartementale de l'**E**quipement et de l'**A**ménagement d'Ile-de-France
GPS	**G**lobal **P**ositioning **S**ystem
IGN	**I**nstitut **G**éographique **N**ational
Insee	**I**nstitut **n**ational de la **s**tatistique et des **é**tudes **é**conomiques
ODP	**O**pen **D**ata **P**aris
OMNIL	**O**bservatoire de la **M**obilité en **Îl**e-de-France
OSM	**O**pen **S**treet **M**ap
SSH	**S**ecure **Sh**ell
UN	**U**nited **N**ations
USA	**U**nited **S**tates of **A**merica

Chapter 1

Introduction

1.1 Motivation

The 2015 Paris agreement by the UN (2015) acknowledges that fundamental changes to societies and economies are necessary to mitigate climate change. With increasing pressure on the transport sector to decarbonise and a better understanding of sustainable transport systems, interest in active modes of transport is growing (Chakhtoura and Pojani, 2016; Mahfouz et al., 2021). Cycling has become increasingly relevant in urban- and transport planning as a cheap, space-efficient, pollution-free, and healthy option to navigate through cities (Chakhtoura and Pojani, 2016; Larsen et al., 2013; Winters et al., 2013). Especially in urban areas, bicycles have the potential to replace motorized modes of transport for short and medium-distance trips (Larsen et al., 2013; Pucher and Buehler, 2012; Winters et al., 2013). Therefore, cities around the world are aiming to increase cycling numbers by implementing sustainable mobility policies. For people to choose the bicycle over other modes of transport, cities need to provide cycling infrastructure of appropriate quality between people's origins and destinations (Mekuria et al., 2012). However, locating streets where improvements of cycling infrastructures are necessary and effective is often not a simple task. To support decision-making, methods to assess bicycle infrastructures are needed.

Paris, the case study area of this project, is not historically known as a cycling city. However, the city has made considerable efforts to improve cycling infrastructures and to become more bicycle-friendly in the past years (Chakhtoura and Pojani, 2016). Several cycling plans such as the *Plan Vélo 2015-2020* with ambitious targets have been introduced. In the COVID-19 pandemic, the implementation of planned measures to improve cycling infrastructures in Paris has been further accelerated to allow more people to travel by bike (Pisano, 2020).

Section 1.2 defines the main objectives and the research questions of this project. Chapter 2 reviews the literature on bicycle transport and the assessment of bicycle infrastructures in urban areas. Furthermore, the two key concepts of this project, bicycle suitability and bikeability are introduced. Chapter 3 examines the case study area, its transport system, recent cycling plans, and common cycling infrastructures and describes the data used in this thesis. The methodology used to address the research questions is explained in Chapter 4. The results of the analysis described and illustrated in Chapter 5 are discussed in Chapter 6. While the discussion aims to answer the research questions, the focus is on reflecting the limitations of the chosen approach and its implications on literature. Finally, Chapter 7 concludes the project and points out future research opportunities.

1.2 Objectives and Research Questions

The core objective of the project is to assess where cycling infrastructures in the city of Paris could be improved. The method identifies potential locations for improvements of cycling infrastructures on a street level and on a city level. The project addresses the need for simple and effective methods to support decision-making in bicycle planning that can be applied using commonly available data. The proposed method has clear outcomes, is reproducible and could be applied to other case study areas.

The research gaps introduced in Section 2.6 lead to the formulation of the following research questions:

- **RQ1**: Where lie the potentials for improvement of cycling infrastructures that increase the bicycle suitability in the city of Paris?
- **RQ2**: How do the potentials change when considering bikeability?

Chapter 2

State of the Art

In the past decades, there has been a surge of interest in cycling as an efficient form of sustainable transport (Larsen et al., 2013; Oldenziel and De la Bruhèze, 2011) and impressive growth of cycling numbers (Oldenziel and De la Bruhèze, 2011; Pucher and Buehler, 2017). This chapter reviews literature on the planning of bicycle infrastructures, transport network analysis, cyclists' route choice, and the assessment of cycling quality in urban spaces. Section 2.1 explores the role of cycling in sustainable urban transport. Section 2.2 reviews literature on the planning of cycling infrastructures. In section 2.3, the main theories of transport network analysis and graph theory are summarized. Factors that influence the route choice of cyclists are explored in section 2.4. Section 2.5 reviews methods that assess bicycle infrastructures in urban areas. This includes the introduction of two key concepts of this project, bicycle suitability and bikeability. Finally, Section 2.6 identifies research gaps that are addressed in this work.

2.1 Sustainable Transport and Cycling

Until recent decades, cycling was not considered a legitimate mode of transport and was largely neglected by transport planners and academics (Pucher and Buehler, 2017). Often, it was excluded from travel surveys and studies (Pucher and Buehler, 2017) that mainly focused on motorized transport. In the interwar period, the bicycle was booming in many European cities (Oldenziel and De la Bruhèze, 2011). Nevertheless, traffic engineers, planners, and policymakers were convinced that cars would inevitably be the dominant mode of transport in the future (Oldenziel and De la Bruhèze, 2011). In postwar reconstruction, the shift towards anti-cycling attitudes was reinforced: Bicycles and their infrastructures were erased from policy agendas (Oldenziel and De la Bruhèze, 2011). Government policies that generally focused on the expansion of roadways and car parking supply were coupled with processes that characterised the 1950s and 1960s in most Western European countries: The increase in motorization level and the sprawling urban development (Pucher and Buehler, 2012). While cars were cast as a modern, progressive symbol of the (USA-inspired) vision of middle-class mobility, bicycles were portrayed as anachronistic and unsafe, the poor-mans mode of transport (Oldenziel and De la Bruhèze, 2011).

Pucher and Buehler (2017) state that the first efforts to promote cycling were in Western Europe, especially in the Netherlands, Denmark, and Germany, starting in the 1970s. Grass-root organizations challenged the technocratic views of traffic planners of the time and demanded a regime shift (Oldenziel and De la Bruhèze, 2011). In several cities, policymakers matched the demands of grass-roots initiatives in the 1970s (Oldenziel and De la Bruhèze, 2011), more European cities adopted similar programs and policies during the 1980s and 1990s, and cities in North America and Australia followed the example in the 2000s (Pucher and Buehler, 2012, 2017). Consequently, the interest in cycling has rapidly grown in transport research and planning since the 1990s (Larsen et al., 2013). Discourses on environmental awareness and the problems caused by car-governed cities led to more bicycle-friendly attitudes (Oldenziel and De la Bruhèze, 2011).

Today, cities around the world are faced with concerns over congestion, air pollution, climate change, physical inactivity, and energy scarcity (Chakhtoura and Pojani, 2016; Larsen et al., 2013; Winters et al., 2010). The fields of public health, urban planning, and transport are therefore developing strategies to tackle transport problems and to move towards more sustainable urban transport systems (Chakhtoura and Pojani, 2016). While the requirements that sustainable urban transport systems should fulfill are not straightforward (Chakhtoura and Pojani, 2016), cycling and walking particularly stand out as sustainable modes of transport. Active modes of transport cause no noise or air pollution, are cheap, space-efficient, and healthy (Larsen et al., 2013; Pucher and Buehler, 2012; Winters et al., 2013). Moreover, bicycles have the potential to replace motorized modes of transport for short trips and medium-distance trips too long for walking (Larsen et al., 2013; Pucher and Buehler, 2012; Winters et al., 2013). Many cities have recognized the importance of cycling as a part of sustainable urban transport and are implementing policies to encourage more cycling (Pucher and Buehler, 2012).

2.2 Planning of Bicycle Infrastructures

Given the growing consensus that cycling is a sustainable mode of transport with various advantages for a city and its people, an important question is how a city can increase cycling numbers. History, culture, climate, and topography influence but don't necessarily determine cycling behavior - government policies are at least as important (Pucher and Buehler, 2008). If a city is aiming to increase cycling numbers, it not only needs to make cycling possible but desirable: Cycling needs to be more attractive than other modes of transport.

To reach the full potential of this transport mode, strategic planning of a complete urban cycling network (as part of a multi-modal transport network) is necessary (Gerike and Jones, 2016). In reality, most cities struggle with the implementation of a complete cycling network, especially in inner urban areas where street space is scarce (Gerike and Jones, 2016) and cycling infrastructures need to be fitted into the existing road network (Parkin and Koorey, 2009). The planning and design of high-quality cycling infrastructures may take decades to complete successfully and arguing for more investments is often more difficult if there already are cycling infrastructures (Parkin and Koorey, 2009). Targeted planning is necessary to complete cycling networks so that they provide safe and efficient access to important destinations (Larsen et al., 2013). For bicycle policies to be successful, they also need to include measures such as traffic calming, education programs, and promotional events (Pucher and Buehler, 2008; Pucher et al., 2010).

The Dutch bike design manual (CROW, 2007) published by the Information and Technology Centre for Transport and Infrastructure proposes five design principles for cycling infrastructures and networks: Safety, directness, comfort, coherence, and attractiveness (see Figure 2.1). Optimizing these characteristics can be considered the aim of cycling infrastructure planning. While the principles apply to all transport networks, they are particularly important for cyclists (Parkin and Koorey, 2009). For example, cyclists are especially vulnerable in traffic and direct paths lead to less physical effort. The degree to which the five principles are met varies greatly between cities but they can be applied to each situation (CROW, 2007). Mekuria et al. (2012) show that cities that have defined strong norms concerning the different principles have proved to attract more cyclists.

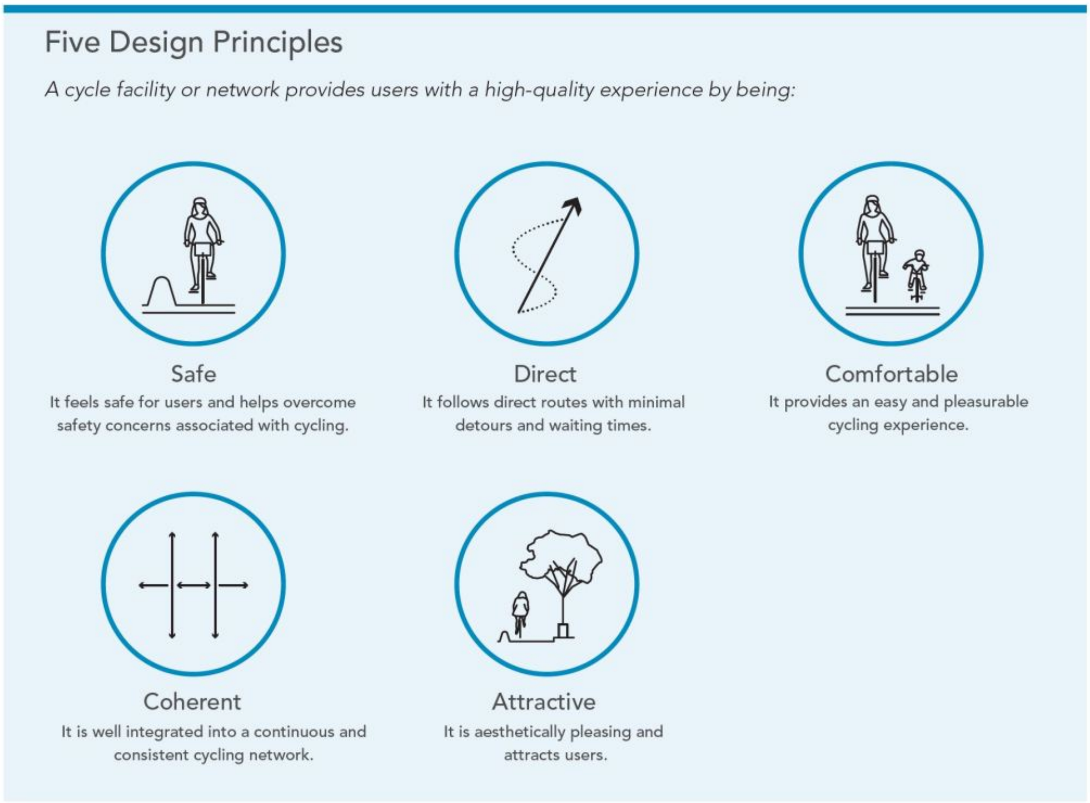


Figure 2.1: The five design principles for cycling infrastructures and networks by CROW (2007). Illustration by Greater Auckland (2017).

However, growth in cycling numbers usually only becomes significant when infrastructures are suitable for a wide range of users (Parkin and Koorey, 2009). Cyclists have varying tolerance for traffic stress (Dill and Mcneil, 2013; Pucher and Buehler, 2021) and exploring different user groups helps to understand what cycling infrastructures they require to choose the bicycle as a mode of transport (Abad, 2019; Mekuria et al., 2012). A classification developed by the city of Portland which was further examined by Dill and Mcneil (2013) defines four different types of cyclists (see Figure 2.2): *Strong & Fearless, Enthused & Confident, Interested but Concerned*, and *No Way No How*. Only 1% of the population is estimated to feel very comfortable cycling without bike lanes and is thus part of the *Strong & Fearless* group. 7% of the population is estimated to be comfortable riding with cycle lanes and are classified as *Enthused & Confident* cyclists. The biggest part of the population, 60%, are estimated to be *Interested but*

Concerned: They are appealed to cycling and would be interested in cycling more, but find it too dangerous. The remaining third of the population is categorised as *No Way No How* meaning that they are physically unable to cycle or not interested in cycling. This classification into four types of cyclists has been widely adopted in the USA (Dill and Mcneil, 2013) and has generated interest internationally in cycling planning. For example, the bicycle observatory of the University of Salzburg is currently working on extensive monitoring of spatial variations of cycling which includes an analysis of types of cyclists to better understand the cycling behavior in the city (Loidl et al., 2020). Efforts to promote cycling often target citizens of the *Interested but Concerned* group which can be thought to be the most important when aiming to achieve growth in cycling numbers (Abad, 2019; Dill and Mcneil, 2013; Pucher and Buehler, 2021). One way of reducing the concerns about safety and traffic of this (large) user group is to provide suitable cycling infrastructures.

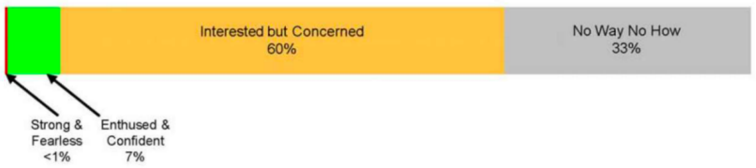


FIGURE 2.2: The four types of cyclists described by Dill and Mcneil (2013). Illustration by Dill (2016).

Literature has shown that appropriate cycling infrastructures are needed to foster a bicycle culture (Larsen et al., 2013; Pucher et al., 2010). Additionally, most research that aimed to evaluate the influence of cycling infrastructures on cycling behavior has found that improving cycling infrastructures has a positive effect on cycling numbers (Grisé and El-Geneidy, 2018; Larsen et al., 2013). For example, Larsen and El-Geneidy (2011) have shown that installing new cycling lanes or paths can direct cyclists onto certain routes. According to Pucher and Buehler (2012), there are four basic types of cycling infrastructures: (1) Stand-alone paths that are often found in parks and are sometimes shared with pedestrians, (2) cycling lanes that physically separate bicycles from motorized traffic by devices such as bollards, planters, or a parking lane, (3) cycling lanes that are marked on the road but do not physically separate cyclists from motorized traffic, and (4) roads where cyclists ride in mixed traffic (can be considered a cycling infrastructure if traffic speed and traffic volumes are low). When trying to improve their cycling infrastructures, cities are faced with decisions on where to install which type of cycling facility.

Defining the appropriate type of cycling infrastructure for a street is not a simple task - researchers and planners have had different opinions and theories about this issue for decades (Broach et al., 2012; Larsen and El-Geneidy, 2011; Parkin and Koorey, 2009). The preferences seem to vary between different user groups and individuals. Since there is a lack of data linking cycling infrastructure to cycling behavior (Broach et al., 2012), much of the evidence about preferences of the appropriate type of cycling infrastructure is based on preference surveys (Broach et al., 2012) and other traditional ways of collecting data using travel diaries, interviews, and static bike counters (Willberg et al., 2021). In their study about lessons for successful cycling planning from the Netherlands, Denmark, and Germany, Pucher and Buehler (2008) found that the two most important approaches to making cycling safe and convenient, are (1) the provision of separate cycling facilities along streets with heavy traffic and at intersections and (2) extensive traffic calming of residential neighborhoods. Similarly, Dill and Mcneil (2013) show that introducing cycling infrastructures that are separated from general traffic and reducing motor traffic speed can increase cycling rates. Larsen and El-Geneidy (2011) argue that separated facilities are the obvious choice in encouraging new cyclists, but that such installations come with high costs. Therefore, the installation of wider, longer and continuous bicycle lane markings might be a more attractive and efficient solution in some cases (Larsen and El-Geneidy, 2011). They further argue that the appropriate type of bicycle facility for a given street is largely dependent on the policy goals of the region (Larsen and El-Geneidy, 2011). Possible improvements and investments of bicycle infrastructures need to be assessed carefully and prioritized according to their importance and effect on the network (Lowry et al., 2016).

2.3 Transport Network Analysis

Transport is an inherently geospatial activity: Continuous geographic space between origin and destination and infinite locations in between are traversed (Lovelace et al., 2019). Transport problems, such as the determination of the optimal location of cycling facilities to best serve the needs of cyclists, often are the motivator of geocomputational methods (Larsen et al., 2013; Lovelace et al., 2019). They involve the creation of transport models that simplify the complex and dynamic transport systems in a way that captures the essence of transport problems (Hollander, 2016). For example, it often makes sense to break continuous space into tangible units - especially origin and destination zones are of interest to transport researchers (Hollander, 2016). Another common representation in transport models are graphs. Transport systems are primarily based on linear features and nodes (Lovelace et al., 2019). In a street network, each road can be associated with an edge in the graph while the vertices correspond to points on the streets such as intersections (Gilardi et al., 2020). The edges may refer to a movement or the mode of transport (e.g. car, bicycle, on foot) between nodes (Abad, 2019). Both the nodes and the edges are associated with spatial geometries, typically points for the nodes and lines for the edges (Gilardi et al., 2020).

The features of a graph might have weights, or costs, assigned to them. Common costs for edges in a street network are their length or the travel time (Bill, 2018). However, the cost might also be subject to more complex functions (Bill, 2018). In a directed graph, the edges have a direction and can only be used in one direction (e.g. edge representing a one-way street) or the cost of an edge is different depending on the direction it is traveled (Bill, 2018). With street networks considered graphs, the geometric elements have topological relations (Bill, 2018). In research, the spatial aspect of spatial networks has often received less attention than their topological properties, even though the topology is strongly constrained by their spatial embedding (Cardillo et al., 2006). For example, the number of edges connected to a node is usually limited by the availability of physical space (Cardillo et al., 2006).

A number of problems can be analysed by representing street networks as graphs. One of them is the shortest path problem which seeks to find the optimal path (or route) between a start and an endpoint (origin and destination) in a spatial network and can be solved using various methods of different complexities (Bill, 2018; Gilardi et al., 2020). For example, the optimal path can be the topologically shortest path using the least possible edges and nodes (Bill, 2018). In a weighted graph, the shortest path is the path with the minimum total cost (e.g. minimum distance or minimum travel time) (Bill, 2018). In tasks such as vehicle navigation, the calculation of optimal or shortest paths has become a standard application (Bill, 2018). Other operations that are commonly applied to street networks to describe their characteristics include connectivity measures and centrality measures (Gilardi et al., 2020). Network connectivity describes how different parts of a network are connected. For example, a graph is said to be connected if a path leads from each node to every other node (Gilardi et al., 2020). The degree of a node counts the number of edges incident to each node (Gilardi et al., 2020). The betweenness is a measure of centrality that estimates the number of shortest paths passing through an edge or a node (Gilardi et al., 2020). Such basic concepts of graph theory are the basis for many network analysis tasks.

2.4 Route Choice of Cyclists

One can assume that cyclists usually choose the shortest possible route (in terms of distance or travel time) between their origin and destination. However, route choice models show that different factors influence the route choice of cyclists and that the routes that cyclists choose are often longer than the shortest path in the network (Broach et al., 2012; Hood et al., 2011). The route choice of cyclists can be analysed by collecting GPS data of cyclists and matching them to the cycling network (Broach et al., 2012; Hood et al., 2011; Menghini et al., 2010; Romanillos et al., 2016; Sener et al., 2009).

Larsen and El-Geneidy (2011) found that cyclists added on average 34% to their trip distance in the city of Montréal, Canada and Broach et al. (2012) found that commuters in Portland, USA added on average 11% to their trip distance. Differences in findings may be attributed to the applied methods which never perfectly reflect the reality of an individual's route choice options (Broach et al., 2012). For example, the methods might include different types of cycling infrastructures or types of cyclists (Broach et al., 2012). Furthermore, it is often difficult to separate the effects of related covariates when modeling the travel behavior of cyclists (Hood et al., 2011). Literature identifies a set of factors of the route and the cyclist as relevant for their route choice (Menghini et al., 2010). The factors include distance, travel time, slope, traffic volume, speed limit, type of intersection, and the presence of cycling infrastructure (Broach et al., 2012; Hood et al., 2011; Menghini et al., 2010). According to Broach et al. (2012), travel times highly correlate with trip distances so that the two factors are more or less interchangeable.

Traffic volumes and speed limits can be used to represent the characteristics of a street (Sener et al., 2009). The two factors have been shown to impact cyclists' comfort and safety. In some studies, the inclusion of traffic volumes is not possible because of data limitations (Menghini et al., 2010). Sener et al. (2009) found that avoiding high traffic situations was one of the two most important factors of route choice (along with minimizing travel times). Broach et al. (2012) state that streets with high traffic volumes and no cycling infrastructures are generally avoided by cyclists. According to their analysis, cyclists are willing to go 36% or 140% out of their way to avoid streets with over 10'000 or 20'000 vehicles per day respectively. Furthermore, Broach et al. (2012) found that low-traffic streets are especially attractive to many cyclists. Surprisingly, Hood et al. (2011) have not detected a significant influence of traffic volume on route choice. Countries and regions often define guidelines to quantify the needed cycling infrastructure for a given traffic situation. For example, according to the Dutch guidelines, cyclists should not have to ride together with motorized traffic where traffic volumes exceed 3'000 vehicles per day or speed limits higher than 30-40 km/h (CROW, 2007).

Bicycle infrastructures can offset the negative effects of adjacent traffic (Broach et al., 2012). Broach et al. (2012) found a general preference for separated cycling infrastructures and state that cyclists are willing to go considerably out of their way to use such infrastructures. As mentioned in Section 2.2, there is a strong consensus in literature that separated cycling facilities should be installed along streets with heavy traffic (Dill and Mcneil, 2013; Larsen and El-Geneidy, 2011; Pucher and Buehler, 2008). While Hood et al. (2011) found a strong preference for cycling lanes (line marking on the street), shared-lane cycling lanes (marked on street but with no line) were slightly preferred to bicycle lanes in the study of Sener et al. (2009). The inconsistency of these two findings is explained by the differences in the design of the two facility types in the two case study areas (San Francisco, USA and Texas, USA).

According to Broach et al. (2012), intersection characteristics can be just as important in terms of route choice as the type of infrastructure on a street. For example, bike boulevards that give bicycles increased priority at intersections are clearly preferred by cyclists (Broach et al., 2012). Sener et al. (2009) found that cyclists prefer routes with fewer stop signs and lights. Dill and Mcneil (2013) state that 68% of bicycle crashes occur at intersections. Generally, intersections are stressful for cyclists, and especially large intersections with no traffic signals are avoided (Grigore et al., 2019; Lowry et al., 2016; Mekuria et al., 2012).

Furthermore, cyclists have been found to detour significant distances to avoid slopes of more than 2% (Broach et al., 2012). Steep slopes of more than 6% are completely avoided if possible (Broach et al., 2012). Broach et al. (2012) state that the slope is one of the most important factors that influence the route choice of cyclists. Hood et al. (2011) have found that cyclists avoid climbing a hill that is 10 meters high if the detour is less than 0.59 kilometers. The study by Menghini et al. (2010) also shows that slopes (specifically the maximum slope rather than the average slope) have an impact on the route choice of cyclists.

There are many more factors that can influence the route choice of cyclists. Some examples are the proximity of green and aquatic areas, the directness of the route, the signalization, the bicycle lane width, the number of turns, the presence of on-street parking, and the weather (Broach et al., 2012; Grigore et al., 2019; Krenn et al., 2015; Lowry et al., 2016; Menghini et al., 2010; Sener et al., 2009). When assessing cycling infrastructures, it can be helpful to consider different influencing factors.

2.5 Assessment of Bicycle Infrastructures

To support decision-making in bicycle infrastructure planning, methods to assess bicycle infrastructures are needed. Various methods have been developed that often reflect the concepts and findings summarized in the previous sections of this chapter. They are usually applied to a specific case study area and are limited by the available data for that area. The lack of cycling data is a common problem in this field of research (Willberg et al., 2021). There is no consistency of terminology describing different measures. In several studies, the central measure is referred to as bikeability (Arellana et al., 2020; Grigore et al., 2019; Krenn et al., 2015; Lowry et al., 2012; Winters et al., 2013) or Bicycle Stress Level (Lowry et al., 2016; Mekuria et al., 2012). In this project, two terms are used (definitions based on Lowry et al. (2012)):

- **Bicycle Suitability**: Perceived comfort and safety of a street segment.
- **Bikeability**: Ability and perceived comfort and safety to access important destinations within the city.

The definitions might seem trivial but they are crucial for understanding the different spatial levels and aspects of cycling infrastructure assessments. While measures of bicycle suitability help identifying specific street segments with lacking cycling infrastructures, they do not allow to draw conclusions regarding the overall cycling network. Even if most street segments of the network are suitable for bicycles, good bikeability is not guaranteed. For example, there might be parts of a city and important destinations that are difficult to reach by bicycle because they are not connected to the rest of the network. In order to support the planning of cycling networks that are of good quality and safety, both bicycle suitability and bikeability should be assessed (Lowry et al., 2012; Rybarczyka and Wu, 2010).

Measures of bicycle suitability typically combine and weigh several relevant and measurable factors that influence the route choice of cyclists described in Section 2.4 (Lowry et al., 2012). The result can then be reflected in a score of bicycle suitability, for example on a spectrum of non-suitable to suitable or 0 to 1 (Lowry et al., 2012). The methods are different in the choice of considered factor and the calculation of the score (Lowry et al., 2012). A common method to assess bicycle suitability is the bicycle level of service (BLOS) described in Landis et al. (1997). It assumes that bicycle facilities should be provided on each street and considers variables such as speed limits, traffic volumes (including heavy truck traffic), and road width (Rybarczyka and Wu, 2010). Factors that are not related to infrastructure characteristics (e.g. slope) are not considered. This and similar measures have been used to assess bicycle suitability for decades and research in this field has remained fairly constant (Lowry et al., 2012). Because travel demand is not considered in bicycle suitability assessments, there is no guarantee that they generate the most desired routes that actually attract more users (Rybarczyka and Wu, 2010). Nevertheless, results of bicycle suitability assessments tend to be very specific and can serve as a basis for further analysis.

One way to assess bikeability is to combine different factors of route choice in a multi-criteria analysis. For example, Terh and Cao (2018) have analysed cycling infrastructures in a planning area of Singapore using a multi-criteria analysis considering nine different criteria such as slope, pedestrian traffic, and proximity to important destinations such as educational institutions or bus stops. The criteria were chosen based on surveys and questionnaires with different stakeholders. Similarly, Winters et al. (2013) identified zones in Vancouver, Canada, where bikeability could be improved based on the analysis of five factors: Bicycle facility availability; bicycle facility quality; street connectivity; topography; and land use. Krenn et al. (2015) have created a bikeability index for the city of Graz, Austria that combines the factors cycling infrastructure, presence of separated cycling infrastructures, main roads without parallel bicycle lanes, green and aquatic areas, topography, and land-use mix. Saghapour et al. (2017) argue that measures of bikeability are mainly limited by the availability of travel behavior data of cyclists. Similarly, Iacono et al. (2010) found that difficulties in calculating bikeability primarily arise from problems with data quality, the zonal structure of transport planning models, and lacking models describing travel behavior of non-motorized travel modes. Furthermore, Winters et al. (2013) point out that the criteria used to determine the indices in such studies are often based on expert opinion or intuition. Therefore, such approaches largely depend on local conditions and policies and are usually not reproducible. Also, the outcomes (often bikeability score per zone) might be difficult to interpret.

Surprisingly, studies that localize weaknesses in the cycling network and systematically prioritize possible improvements are quite limited. Larsen et al. (2013) proposed a method to locate facilities with lacking bicycle suitability using origin-destination data from an extensive travel survey, a cycling survey, and collision data from an accident database to locate and prioritize locations for new cycling infrastructure in Montréal, Canada. The study mainly focuses on identifying and prioritizing locations for new cycling infrastructures - improvements in the existing cycling infrastructures due to insufficient bicycle suitability are not considered. A similar method with a focus on the distribution of infrastructures and who benefits from them was developed by Grisé and El-Geneidy (2018) and applied to the city of Québec, Canada. Arellana et al. (2020) proposed an index that includes factors for each of the five design principles by CROW (2007), e.g. slope of bike lanes and width of bike lanes as indicators for comfort and attractiveness, traffic flow for safety, bike traffic flow, and traffic lights for security. The study uses origin-destination data and surveys amongst different types of cyclists. Based on the estimated cycling flows generated in the bikeability calculations, they then assessed the priority level of different investments (Arellana et al., 2020). The *Propensity to Cycle Tool* developed by Lovelace et al. (2017) is an online interactive planning tool that allows the prioritization of investment in cycling infrastructures. It models cycling levels and desired lines based on travel surveys and was first created to explore and map cycling potentials across England but can increasingly be implemented in new contexts (Lovelace et al., 2017). These measures rely on data from extensive travel surveys and/or surveys amongst different groups of cyclists. Therefore, such analyses are often not reproducible and the outcomes might vary depending on the design of the surveys and the data collection processes.

Another approach to measure bikeability is to apply measures of accessibility, a concept that is typically defined as the ease of reaching important destinations (Hansen, 1959; Iacono et al., 2010; Lowry et al., 2012). While many studies limit their focus on access to employment, other types of destinations (e.g. retail, recreation) can also be considered (Iacono et al., 2010). Accessibility can be considered a function of the spatial separation between places: Farther away implies lower accessibility (Saghapour et al., 2017). Some measures of accessibility can be used to calculate the distance to the closest destination or the number of destinations within a defined distance (Saghapour et al., 2017). Other accessibility measures, so gravity-based or Hansen-type (Hansen, 1959) measures, consider a travel impedance such as distance, travel time, or cost between the origin and possible destinations (Saghapour et al., 2017). Even though accessibility measures have mostly been applied in the planning of motorized transport, they can be constructed for bicycle planning as well (Iacono et al., 2010). In fact, accessibility by non-motorized modes of transport has emerged as an important topic in transport and urban planning (Saghapour et al., 2017).

Grigore et al. (2019); Iacono et al. (2010) and Lowry et al. (2012) have developed methods to assess bikeability based on a Hansen-type measure of accessibility that take into account bicycle suitability on the route between origins and destinations. Mekuria et al. (2012) proposed a method with a focus on low-stress (streets suitable for bicycles) connectivity of bicycle networks that allowed to identify and prioritize specific locations for new cycling infrastructures in the city of San Jose, USA. Lowry et al. (2016) introduced a similar method to prioritize bicycle improvement projects. In this study, accessibility scores are computed for each parcel in the study area of Seattle, USA and the improvements are prioritized to best improve low-stress network connectivity (Lowry et al., 2016). Both of these studies first assess factors that influence bicycle suitability such as the number of vehicle lanes, speed limits, and bike lane width, and then conduct an accessibility evaluation based on the results. By assessing both bicycle suitability and bikeability it is possible to analyse different aspects of bicycle infrastructures.

2.6 Research Gaps

The literature review has unveiled several research gaps:

(1) Many of the described methods require data that is not commonly available and can therefore not be applied to other case study areas.

(2) Only few studies assess bicycle suitability and bikeability separately. Doing so can be helpful to gain a better understanding of potential locations for improvements of cycling infrastructures on both a street level and on a city level.

(3) Studies that have assessed bicycle infrastructures in the city of Paris do - to the knowledge of the author - not exist.

This project proposes a method that assesses where cycling infrastructures can be improved and tries to close the identified research gaps. The method can be applied with commonly available data and has clear outcomes. Both bicycle suitability and bikeability are assessed in the city of Paris. Using a fully reproducible approach, the method could also be applied to other case study areas. The research gaps lead to the formulation of the research questions as stated in Section 1.2:

- **RQ1**: Where lie the potentials for improvement of cycling infrastructures that increase the bicycle suitability in the city of Paris?
- **RQ2**: How do the potentials change when considering bikeability?

Chapter 3

Case Study Area & Data

This chapter introduces the case study area and the data used for this thesis. In the past years, there have been considerable efforts to improve cycling infrastructures in the city of Paris which makes it an interesting case study area for this project. Section 3.1 examines the transport system, recent cycling plans and policies, and common cycling infrastructures in Paris. These topics provide an interesting background for the analysis and the discussion of results in the following chapters. The data used in this thesis and other data sets that have been considered are described in section 3.2.

3.1 Case Study Area

The city of Paris has been selected as the case study area for this project. Paris is considered a tourist's dream - a beautiful, historic, culturally rich, and enchanting city. The river Seine splits the city into two parts, the *Rive Droite* to the north and the *Rive Gauche* to the south. Paris can be considered a mosaic of its twenty *arrondissements* - administrative districts that can often be characterised as predominantly historic, touristic, economic, commercial, or residential (Apur, 2020). The population of the city of Paris has been decreasing in the past decades but has stabilised at around 2.2 million people in the past years (Insee, 2017). With an average of over 20'000 inhabitants per square kilometer, it is one of the most densely populated urban areas in Europe (Apur, 2020; Insee, 2017). The city spans roughly 9.5 kilometers from north to south and 12 kilometers from east to west (Apur, 2020).

The city of Paris is the center of the capital region of Île-de-France (see Figure 3.1), which consists of the city of Paris (department 75), *Petite Couronne* (ring of three departments around the city of Paris), and *Grande Couronne* (second outer ring of four departments around *Petite Couronne*). The *Boulevard Périphérique*, a busy motorway with up to four lanes, is situated along the administrative limit of the inner city and thus can be seen as one of the physical limits of the city (Apur, 2020). The region of Île-de-France had a population of over 12 million people in 2016 (OMNIL et al., 2020) and usually ranks among the most economically developed urban areas worldwide (Apur, 2020).

The distinctive structure of the streets in Paris can be traced back to Haussmann, an official who carried out a radical urban renewal program in Paris in the 19th century (Apur, 2020). The program included the construction of new wide boulevards, squares, and public works such as aqueducts, canalisations, train stations, town halls, and parks (including the two city parks *Bois de Vincennes* to the east and *Bois de Boulogne* to the west) (Apur, 2020). The renovation by Haussmann dominates the cities appearance until today (Apur, 2020).

3.1.1 Transport in Paris

To understand mobility patterns in Paris, it is important to consider the numbers of trips and the modal share (percentage of trips per transport mode) of different transport modes. The *Observatoire de la mobilité en Île-de-France* (OMNIL) publishes travel surveys for the Île-de-France region every ten years, the most recent survey covers the 2018-2022 period and the first results have been published in January 2020 (OMNIL et al., 2020). On average, inhabitants of the Île-de-France region cover a distance of 18 kilometers per day and spend 1 hour and 30 minutes moving. However, two-thirds of all trips are short: They cover less than 3 kilometers and take less than 30 minutes. In total, 43 million trips are made each day in the Île-de-France region, over 70% of which take place entirely outside of Paris city, where people tend to make more trips with shorter distances throughout the day (see Figure 3.1).

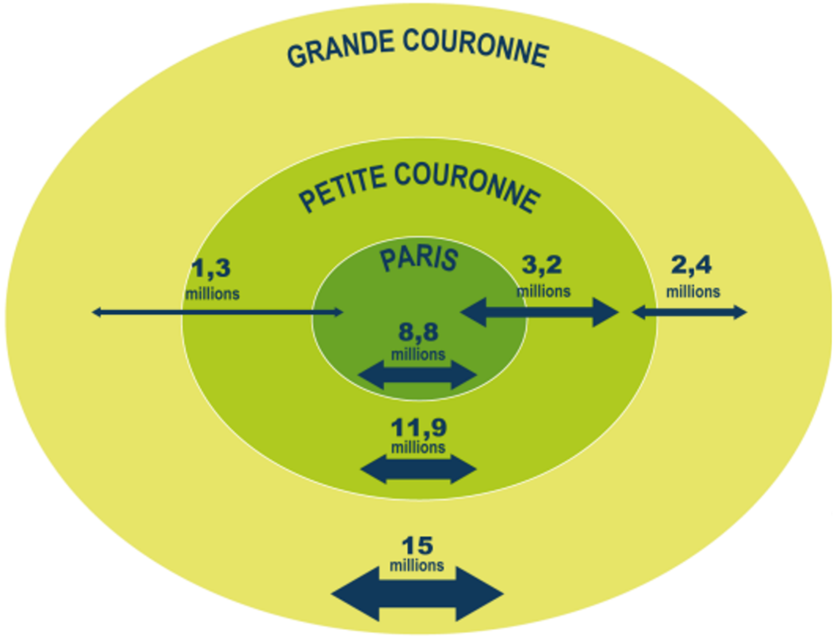


FIGURE 3.1: The Île-de-France region with the city of Paris (case study area) in the center. Number of trips (all modes of transport) in the Île-de-France region. Illustration by OMNIL et al. (2020).

While walking is the most common mode of transport in Paris city and *Petite Couronne* (about 40% of all trips in Île-de-France), the car is the predominant mode of transport in *Grande Couronne* (roughly 35% of all trips in Île-de-France). Most car trips, however, take place entirely outside of the city of Paris where less than 5% of trips are made by car (OMNIL et al., 2020). Public transport makes up 22% of trips in the Île-de-France region with numbers continuing to rise since 2000 after being stagnant for some decades (OMNIL et al., 2020). Paris has one of the busiest metro systems in the world - it consists of 16 lines that serve over 300 stations (Nair et al., 2012).

In the past two decades, the city of Paris has made considerable efforts to become more sustainable in terms of transport (Chakhtoura and Pojani, 2016) by introducing urban policies that favor public transport and active modes of transport (Côme and Oukhellou, 2014). Since 2000, the city of Paris and the government agency *Syndicat des Transports d'Île-de-France (STIF)* have created seven plans related to urban transport (Chakhtoura and Pojani, 2016). They have led to substantial achievements in terms of sustainable transport targets such as a noticeable shift from private cars to public transport and other modes (Chakhtoura and Pojani, 2016). This shift is also reflected in the latest travel survey by OMNIL et al. (2020). Compared to previous surveys, the modal share of public transport and active modes of transport has increased significantly between 2010 and 2020 (OMNIL et al., 2013, 2020).

The structure and geography of the city of Paris is generally well suited for cycling: Distances in the densely built city are comparably short and the wide boulevards from the Haussmann renovation generally provide plenty of street space for different modes of transport. In the Île-de-France region, the number of daily cycling trips has doubled between 2001 and 2010 to over 650'000 trips and between 2010 and 2019 the number of trips per day has grown by almost a third to 840'000 (OMNIL et al., 2013, 2020). In 2007, the bike-sharing system *Vélib'* was launched and has since grown to become the largest bike-sharing system in Europe and one of the largest worldwide (Côme and Oukhellou, 2014; Nair et al., 2012). *Vélib'* has a fleet of about 20'000 bicycles spread across roughly 1'400 stations that are mainly located in the city of Paris (Nair et al., 2012). About 30%-35% of cycling trips in the city of Paris are made using the bike sharing-system (Mairie de Paris, 2015; OMNIL et al., 2013). However, with a modal share of under 2%, the bicycle is only a marginal mode of transport in Paris (Apur, 2020). It is mainly used for short distances: Almost 80% of cycling trips cover a distance of under 3 kilometers and 92% if trips are of a distance under 5 kilometers (Eloy and Derré, 2014). Most cycling trips are commutes between home and workplace (40% of all cycling trips) - the modal share of cycling for communing trips is 4% (OMNIL et al., 2020). According to the Mairie de Paris (2015), about 40% of all cyclists in the city of Paris are female, 7% are less than 20 years old and 16% are over 60 years old. There are a number of interest groups such as *Mieux se Déplacer en Bicyclette (MDB), Vélorution* and *Paris en Selle* that aim to foster and improve the cycling culture in Paris.

The COVID-19 pandemic has had an enormous impact on travel behavior around the world (Buehler and Pucher, 2021). After the first cases in Europe were reported in Italy in early 2020, large cities such as Madrid, London, and Paris rapidly became epicenters of the pandemic (Pisano, 2020). Île-de-France mobilités (2021) has published a survey on the changes in travel behavior in the region of Île-de-France. Compared to the 2018 survey, the number of trips has decreased by 25% - especially the number of trips using public transport has dropped impressively (Île-de-France mobilités, 2021). The number of bicycle trips has increased especially in the city center but the bicycle modal share stays modest (Île-de-France mobilités, 2021). In terms of user groups, the growth of cycling numbers can be traced back to predominantly male users, especially people working in cadre positions and students (Île-de-France mobilités, 2021). Some measures concerning cycling infrastructures that were implemented in Paris as a reaction to the pandemic are described in the next section. Buehler and Pucher (2021) argue that the increase in cycling during the COVID-19 pandemic is likely to persist over the coming years.

3.1.2 Cycling Plans and Policies

There have been considerable efforts to improve the cycling culture in Paris in the past two decades (Chakhtoura and Pojani, 2016). While the urban transport plans that have been evaluated in the study by Chakhtoura and Pojani (2016) have different thematic focuses, all of them include measures to improve the quality, comfort, and safety of cycling infrastructures. The last cycling plan in Paris, the *Plan Vélo 2015-2020* aimed to make Paris a *cycling capital* with investments of 150 million euros (La Ville de Paris, 2021). The goal of the cycling plan was to provide a continuous and secure cycling network that allows everybody to move easily by bike (Copenhagenize Index, 2019). According to the Mairie de Paris (2015), different public surveys (e.g on the preferred type of cycling infrastructure) and the results of an evaluation of the previous cycling plan were considered. The most important goals of the plan were to triple the cycling modal share to 15%, to double the cycling route kilometers, to install additional bike-only corridors, and to create a long-distance express network (La Ville de Paris, 2021). Furthermore, the *Plan Vélo 2015-2020* included measures such as the improvement of signalization, and additional bike parking (La Ville de Paris, 2021). The aims were very ambitious and fit well into the series of policies of Mayor Anne Hidalgo (first elected in 2014) that banned the most polluting vehicles from entering the city, freed the riverside from cars, and regained street space for more trees and pedestrian space (Pisano, 2020).

The strategy of the *Plan Vélo 2015-2020* involved the allocation of streets to different types of cycling networks (see Figure 3.2) according to their functions and what type of cycling infrastructures should be provided on them (La Ville de Paris, 2021; Mairie de Paris, 2015):

- The **express network** (*Réseau express vélo (REVe)*) crosses the city from north to south and from east to west (connecting the *Bois de Vincennes* in the east with the

Bois de Boulogne in the west following the river Seine). These are wide cycling lanes that are physically separated from motorized traffic and should guarantee comfort and security for cyclists.

- The **structuring network** (*Réseau structurant*) is organised around the express network and includes three additional main axes circling the city. These are bidirectional cycling paths that are physically separated from motorized traffic.
- The **secondary network** (*Réseau secondaire*) completes the structuring network and has the goal of covering the city area by providing fine-lined connections between infrastructures of the structuring network. These cycling infrastructures also cross bridges, squares, and the gateways of the city to allow connections to the neighboring departments outside the city limits.
- The city is progressively transforming its territory to ***Zones 30*** with speed limits of 30 km/h. In these areas, bidirectional cycling paths are systematically installed in one-way streets.

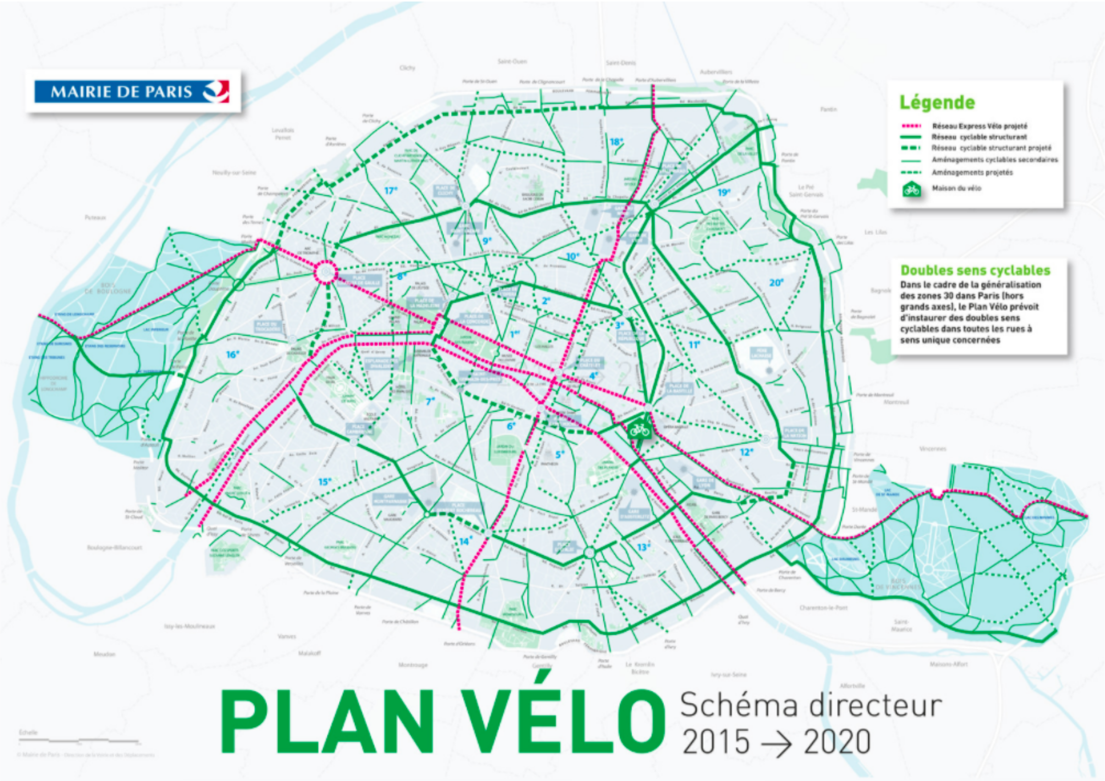
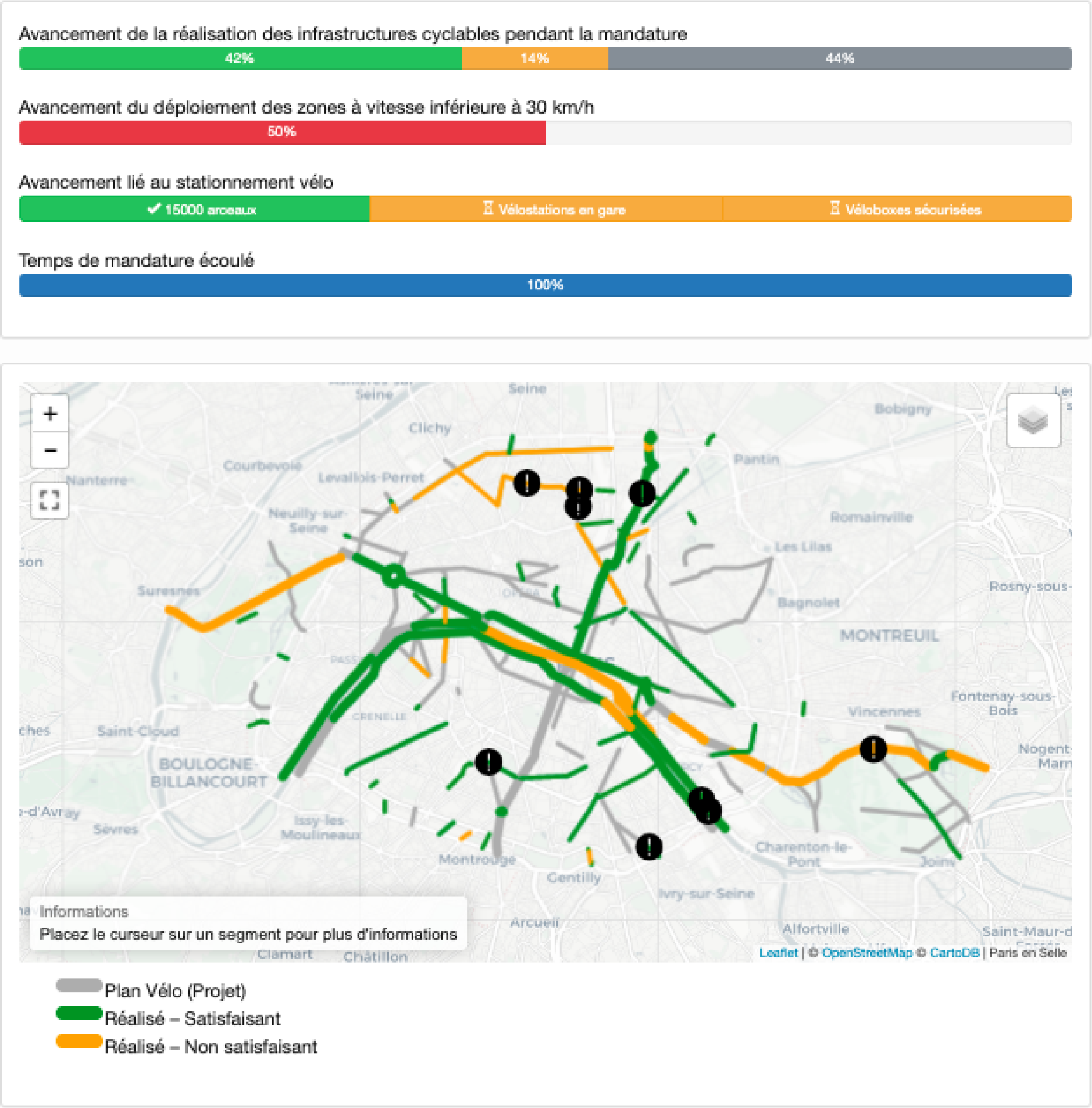


Figure 3.2: The *Plan Vélo 2015-2020* with its different components.
Pink lines: Express network, green bold lines: Structuring network, green lines: Secondary network, dashed lines: Projected cycling infrastructures. Illustration by La Ville de Paris (2021).

There has been considerable progress that can be attributed to the *Plan Vélo 2015-2020*. According to La Ville de Paris (2020), the streets that have been transformed to *Zones 30* in 2018 and 2019 allowed to install bidirectional cycling lanes of type *Double sens cyclable* on 200 street kilometers. These cycling infrastructures are thought to offer comfortable and safe conditions for cyclists. La Ville de Paris (2020) also states that all of the city of Paris apart from the main axes should be transformed to *Zones 30* by 2020. Similarly, more and more areas are transformed into *Zones de rencontre* with speed limits below 30 km/h that serve as mixed-used zones where pedestrian and cycling transport are prioritized (Mairie de Paris, 2015). Furthermore, the website of La Ville de Paris (2020) shows some examples of newly installed cycling infrastructures (e.g. the new express routes on *Voie Georges Pompidou* and *Rue Rivoli*).

However, not all goals of the *Plan Vélo 2015-2020* have been reached in its duration period. As part of the project Observatoire du Plan Vélo (2020), the interest group *Paris en Selle* assesses the advancements of the measures of the cycling plan (see Figure 3.3). They provide an interactive map that illustrates the projected streets and whether they are satisfactory for cycling. According to their assessment, 42% of the planned bicycle kilometers are installed satisfactory, 14% are installed non-satisfactory, and 44% are not realised. Furthermore, they estimate that only half of the areas that were supposed to be transformed into *Zones 30* have been converted successfully by the end of the plan duration (Observatoire du Plan Vélo, 2020). This example shows that evaluations by the city do not always match evaluations carried out by interest groups.

The measures of the *Plan Vélo 2015-2020* still seem to be in progress even though the plan duration has expired (La Ville de Paris, 2021). The Observatoire du Plan Vélo (2020) also shows infrastructures that have been installed after the expiration of the cycling plan. In the COVID-19 pandemic, the measures have been further accelerated and some improvements have been pushed through as emergency measures to allow more people to commute by bike (Pisano, 2020). In Paris, the cycling network was expanded by 80 kilometers within a very short time in 2020, 55 kilometers of which were specifically designated as *Coronapistes* (Corona bike lanes). Furthermore, traffic-calming measures were expanded and some streets (most famously *Rue Rivoli*, a major street in the city center of Paris) were completely freed from motorized transport (Buehler and Pucher, 2021).



Avancement de la réalisation des infrastructures cyclables pendant la mandature

42% | 14% | 44%

Avancement du déploiement des zones à vitesse inférieure à 30 km/h

50%

Avancement lié au stationnement vélo

✓ 15000 arceaux | ⌛ Vélostations en gare | ⌛ Véloboxes sécurisées

Temps de mandature écoulé

100%

Informations

Placez le curseur sur un segment pour plus d'informations

Figure 3.3: Assessment of the advancements of the *Plan Vélo 2015-2020* by the interest group *Paris en Selle*. Screenshot from Observatoire du Plan Vélo (2020), 20/08/2021.

Hildago's campaign *Paris en Commun* for the 2020 re-election has since been relaunched as a post-COVID strategy (Pisano, 2020). It includes the concept of a *15 minute city*, according to which the basic needs of citizens (work, shopping, health, culture, etc.) should be available within 15 min of their home - a concept in which more road space would be dedicated to bikes and pedestrians (Pisano, 2020). Another goal has been set by Hidalgo: To make 100% of the streets in Paris cyclable by 2024 (Paris en Commun, 2020). The general trend is clear: Paris wants to become a cycling city (La Ville de Paris, 2021) and improving the cycling culture in Paris is an integral component of Hidalgo's program and policies (Paris en Commun, 2020; Pisano, 2020). A new urban transport plan favoring public transport, cycling, and professional motorized vehicles is currently being developed (Paris en Commun, 2020). Amongst other measures, the plan will presumably push forward the generalisation of *Zones 30*, aim to create at least one cycling street per neighborhood, and ensure the installation of cycling infrastructures on all bridges to improve the connection of the city of Paris and neighboring departments and across the river Seine (Paris en Commun, 2020). There has already been some progress concerning the first point: In July 2021 it has been announced more streets will be transformed to *Zones 30* by the end of August 2021 (Le Parisien, 2021). Only very few streets with higher speed limits would remain in the inner city making the city safer and calmer (Le Parisien, 2021).

The recent efforts of the city of Paris to improve cycling infrastructures and to foster the cycling culture have received a lot of attention. The efforts of the past years also show in the Copenhagenize Index (2019), a ranking of bicycle-friendly cities, where Paris has moved up several ranks between 2017 and 2019. Their website states that Paris has gained new momentum and is finally building out dedicated cycling infrastructures. Generally, Chakhtoura and Pojani (2016) have observed considerable progress in non-motorized transport planning in Paris: The cycling network has expanded and cycling rates have increased. The COVID-19 pandemic has further accelerated this trend and it can be assumed that the city will continue to improve its cycling infrastructures.

3.1.3 Common Cycling Infrastructures

Figure 3.4 shows the common types of cycling infrastructures in Paris. The *Double sens cyclable* allows for cycling traffic in both directions on one-way streets with a speed limit of 30 km/h. According to La Ville de Paris (2021), most one-way streets in residential areas with a speed limit of 30 km/h are designed this way to reduce accidents and to prioritize cyclists and pedestrians. The *Bandes cyclables* are cycling lanes with simple paint markings on the streets. This type of infrastructure tends to get blocked for parking or parking maneuvers, especially in dense urban areas, and does not satisfy many cyclists in terms of safety (Paris en Selle, 2018). The *Couloirs de bus ouverts aux vélos* are shared bus lanes that can be used by taxis and bicycles as well (La Ville de Paris, 2021). This type of infrastructure is often found on streets with a speed limit of 50 km/h where riding on the same lane as buses is stressful for many cyclists (Paris en Selle,

(a) Double Sens Cyclable

(b) Bande Cyclable

(c) Couloir de Bus Ouvert aux Vélos

(d) Piste Cyclable

Figure 3.4: Common types of cycling infrastructures in the city of Paris: *Double sens cyclable* (a), allows cycling in both directions in one-way streets, common in *Zones 30*; *Bandes cyclables* (b), marked cycling lanes, *Couloirs de bus ouverts aux vélos* (c), shared bus lanes; *Pistes cyclables* (d), physically separated cycling lanes.

2018). Therefore, this type of cycling infrastructure is increasingly transformed into separated cycling lanes (*Pistes cyclables*) that are physically separated from motorized traffic (Copenhagenize Index, 2019). An internet survey by the Mairie de Paris (2015) confirms that separated cycling infrastructures (*Pistes cyclables*) are usually preferred by cyclists compared to other types of cycling infrastructures.

The *guide des aménagements cyclables*, published by Paris en Selle (2018), formulates guidelines for cycling infrastructures in Paris. They state that an important principle to follow is *Separation & Efficiency*. They argue that about 80% of the street network in the city should carry very little motorized traffic (2'000 vehicles per day or 200 vehicles in peak hours). Furthermore, it is mentioned that traffic speed should be kept low in the calm zones so that the space can be shared between all road users and no cycling infrastructure is needed. While marked cycling paths might not be necessary along streets with that little traffic, they can be helpful close to intersections, where traffic volumes tend to be higher. Above the mentioned threshold, motorized traffic causes too much stress for most cyclists. On these streets, mainly along the main street axes, bicycles should be physically separated from motorized traffic. Since such facilities are rather cost-intensive, Paris en Selle (2018) proposes traffic-calming measures where possible. The guidelines reflect some important findings from research in bicycle infrastructure planning (see Section 2.2). They are largely inspired by particularly bicycle-friendly cities in the Netherlands and Denmark and might seem too ambitious or even unrealistic for some (Paris en Selle, 2018). However, some of the guidelines have certainly influenced current cycling plans.

After describing the most common types of cycling infrastructures, it is also important to consider some problems and discontinuities that can be frequently observed in Paris. A survey with over 7'000 participants that frequently cycle in Paris unveiled three main issues: (1) Parked cars blocking cycling infrastructures, (2) the lacking continuity of the cycling infrastructures, especially at intersections, and (3) missing bicycle parking (Paris en Selle, 2017). Examples for the first two issues are shown in Figure 3.5. Furthermore, the Copenhagenize Index (2019) states that attention needs to be paid to the details of infrastructures: Their connection at intersections and how they can be used by users of all ages and abilities. As the previous section has shown, the city of Paris seems to have acknowledged some of these issues and it can be expected that further policies to improve cycling in Paris will be introduced in the coming years.

(a)

(b)

Figure 3.5: Two common issues when cycling in Paris: Parked cars blocking cycling infrastructures (a) and lacking continuity of cycling network at intersections (b).

3.2 Data

In this analysis, it was assumed that cycling is possible on all streets. Therefore, the cycling data needs to include all streets of the case study area with additional information on their characteristics (e.g. the type of cycling infrastructures provided). Two main data sources were used in this project: OpenStreetMap (OSM) and Atelier parisien d'urbanisme (Apur). This section explores different data sources that have been considered for the analysis. This is particularly relevant because the absence of applicable data often limits transport and urban planning studies that focus on cycling (Willberg et al., 2021). An overview of the data used in this project and their sources is shown in Appendix A.1.

Originally, it was planned to use data from Open Paris Data. The platform provides both complete and up-to-date data of cycling infrastructures and road data with all streets in the city (Open Data Paris, 2021). The road data stores the geometry of the center-line of each road and includes topological information. The cycling infrastructures, however, are stored with their precise geometry (e.g. on both sides of a given street and/or ending before the intersection). While this very accurately represents cycling infrastructures, the cycling infrastructure data can not be used for topological analysis. The two data sets do not share a common attribute. Therefore, assigning the cycling infrastructures to the corresponding road segment would have demanded a map-matching algorithm. Because of this important limitation, Open Paris Data was not used as a data source in this project. Furthermore, data from the French National Mapping Agency (*Institut Géographique National*, IGN) was considered for the analysis. It provides road data in their Route 500 data which covers the country of France (IGN, 2016). However, this data is not suited for this project, because it only stores information on roads for motorised traffic (mostly on a national and regional scale) and does not include information on cycling routes apart from the national long-distance cycling routes (IGN, 2016). Therefore, this option was also discarded.

Finally, OpenStreetMap (OSM) was chosen as the main data source for this project. OSM is a collaborative mapping project that started in England in 2004 and provides free and editable geographic information of the world (Abad, 2019; Hochmair et al., 2013). The natural and built environment is mapped in OSM, including transport infrastructures (Nelson et al., 2020). The mapping process is based on the crowdsourcing of geographic information and everyone (from amateurs to experienced cartographers) can contribute to the project (Goodchild, 2007). It can be described as a continuously updated database, always providing the latest data to download (Girres and Touya, 2010). OSM data can be used for a wide range of applications such as mapping, geographic analysis, and urban planning (Girres and Touya, 2010; Nelson et al., 2020). The interest in the project has grown considerably over the years (Goodchild, 2007). One of the main advantages is that OSM provides a single global data source which makes it an interesting data source for research, also at national or global scales (Nelson et al., 2020).

Data uploaded into OSM by contributors of the project are stored in tagged geometric features (nodes, lines, or relations) with assigned attributes commonly referred to as tags (Girres and Touya, 2010; Touya et al., 2017). For example, a cycling lane might be stored as a line feature with tags highway = *cycleway*, oneway = *no*. There are precise specifications that list the accepted tags and fields of values according to best practice on tagging (Girres and Touya, 2010; Hochmair et al., 2013). The coding conventions for bicycle infrastructures and the options for their mapping are becoming more and more detailed (Hochmair et al., 2013). A major advantage of this tagging structure is that the data is relatively homogeneous for the whole world (Hochmair et al., 2013). However, the tagging specifications are not enforced and contributors can submit new tags or values (Hochmair et al., 2013). Therefore, the same feature (e.g. a cycling path) might be tagged in different ways depending on the user (Hochmair et al., 2013). Because of the way that the data is acquired, data quality and data consistency are important limitations of OSM data. Many studies deal with the assessment of data quality of OSM data, also in comparison with institutional reference geographic databases (Girres and Touya, 2010; Hochmair et al., 2013). Few studies have specifically assessed the completeness of OSM cycling data (Hochmair et al., 2013). Several studies suggest that OSM data has often been found to be more up-to-date than city data (Nelson et al., 2020). Hochmair et al. (2013) note that OSM data is becoming more complete and appropriate to be used as a base map for planning studies on non-motorized transport. However, Hochmair et al. (2013) recommend checking the data against other sources before conducting an analysis.

In the case of Paris, there were noticeable differences between the OSM cycling infrastructure data and data from other sources such as Apur and Open Paris Data. Therefore, the data by Apur (2020) was used to supplement the OSM data. The data set was created in 2020 for a project coordinated by *Île-de-France Mobilités* in collaboration with the region of Île-de-France, Apur, *Institut Paris Région*, and regional and local authorities (Apur, 2020). It is based on OSM road data but has been completed specifically to assess cycling infrastructures (Apur, 2020). The data provides more details on the type of infrastructure than the OSM base data does: Cycling infrastructures are classified into ten different types of infrastructure (e.g. *Bande cyclable et voie de bus partagée, Voie de bus partagée unidirectionnelle, Piste cyclable unidirectionnelle* and *Autre aménagement cyclable partagé*). It is assumed that by combining the two data sets, a more complete representation of bicycle facilities in Paris could be obtained.

Since OSM only allows the download of a limited amount of data at a time, the third-party website Geofabrik was used for the download. The data includes different layers such as buildings, waterways, transport, points of interest, and roads for the Île-de-France region. In this project, the layers roads, transport, and points of interest (describing places of interest such as touristic places, amenities, and shops which are tagged accordingly (Touya et al., 2017)) were used. Furthermore, the district borders (*arrondissements*), the waterways, and the park geometries were downloaded from the Apur geoportal (Apur, 2020). A digital elevation model (DEM) with altitude information is provided by IGN in an open-source format. The data (BD Topo) with a resolution of 75 meters was downloaded from the IGN (2021) geoportal for the department of Paris. All data was downloaded between the 01/02/2021 and the 05/02/2021.

Chapter 4

Methodology

4.1 Overview

This chapter describes in depth the methodology of this project. It consists of three main processing steps illustrated in Figure 4.1. In the preprocessing step explained in Section 4.2, the two cycling data sets from OSM and Apur are joined and filtered. The resulting cycling data is used as base data for the analysis. In the second processing step described in Section 4.3, the bicycle suitability of each street segment is assessed considering the available cycling infrastructure and the speed limit. A bicycle suitability multiplier and a slope multiplier are used to calculate the perceived distances for further analysis. In the third processing step (Section 4.4), origins and destinations are modeled and bikeability is assessed on a city level. The proposed methodology is applied to the case study area of Paris and addresses the research questions introduced in Section 1.2.

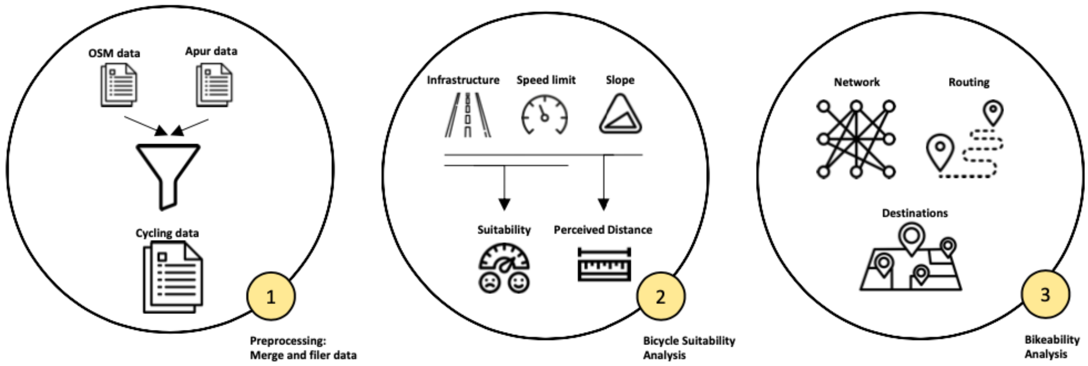
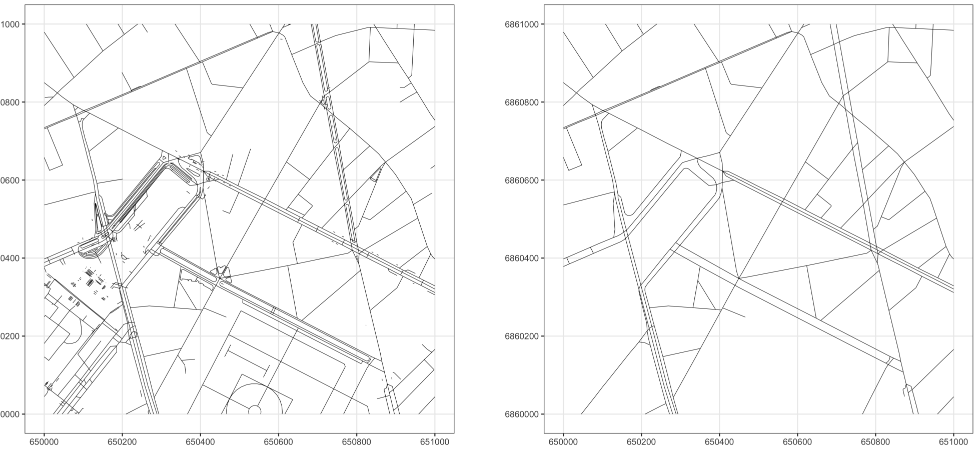


FIGURE 4.1: Overview of the three main processing steps: (1) Preprocessing, (2) Bicycle Suitability Analysis, and (3) Bikeability Analysis. Icons from Flaticon (2021).

For data preprocessing, data analysis, and visualisation, R was used exclusively as software in this project. It is an open-source language for statistical computing and graphics which is extended by packages that address different data analysis questions in various fields of research (R Core Team, 2020). R is an increasingly popular programming language for geographical data and network analysis (R Core Team, 2020) and the spatial ecosystem is rapidly evolving (Lovelace et al., 2017). R version 3.6.1 and the Integrated Development Environment (IDE) RStudio version 1.2.1335 were used for this project.

4.2 Preprocessing

This section describes the creation of the cycling infrastructure data which was used as the basis for all further analysis. Two data sets were combined: OSM street data and cycling infrastructure data from Apur. If only OSM data were used, the preprocessing would be quite straightforward since R provides packages that allow directly downloading OSM data. However, due to the data quality advantages of the Apur data described in Section 3.2, this additional preprocessing step was necessary. Figure 4.2 illustrates the cycling infrastructure data before and after preprocessing.



(a)

(b)

FIGURE 4.2: Cycling data before (a) and after (b) preprocessing.

First, all data was converted to the Lambert-93 coordinate system (epsg code 2154), the projected coordinate system for France. While the Apur data is provided in the Lambert coordinate system, OSM data is downloaded in a WGS84 projection (epsg code 4326). Then, the OSM and the Apur data were cropped to the city borders using the polygon shape of the *arrondissements.* The two data sets were then merged by the *osm id* (possible because Apur data is based on OSM data). The *osm id* is a unique integer in the OSM data that represents an OSM feature. For example, each line feature has its unique *osm id* and represents a street segment. One street can consist of multiple line features with different attributes and geometries, each with a unique *osm id.* In the resulting data, all cycling infrastructures from the Apur data are assigned to a feature of the OSM data. The cycling infrastructures from Apur can have different geometries than the OSM data (even if the *osm id* is matching) and more than one feature from the Apur cycling infrastructure data can have the same *osm id* if multiple cycling infrastructures are assigned to one street. In the next step, features with an equal geometry were removed. These are cycling infrastructures that have the same geometry as the OSM data and only one of the items, the one with the cycling infrastructure information, needs to be retained.

Then, the data was cleaned so that it best serves the purpose of the analysis. Cycling infrastructures in the two city parks *Bois de Vincennes* to the east and *Bois de Boulogne* to the west were removed. They are not relevant for this project since the focus lies on urban cycling and not on recreational cycling. The concerned streets were removed by intersecting the street data with park data from Apur. Furthermore, street types that are not relevant to the analysis were removed from the data: Pedestrian streets such as steps or small footways and motorways such as the *Péripherique* surrounding the city were removed by filtering the corresponding street classes from the OSM street attribute (highway tags *path, footway, pedestrian, service, steps, motorway, motorway_link, trunk*, and *trunk_link*). The filtering of the mentioned streets also allowed to significantly reduce the number of streets in the data.

In the next step, the streets were split at their intersections using small buffers. The approach was inspired by an entry on Stackoverflow (2019). The attributes from the streets were assigned to the newly created geometries. In the resulting data, a new street segment is defined at each intersection or change of infrastructure. The cycling data holds 25'387 street segments. It contains information on street characteristics such as speed limit, road type, and type of cycling infrastructure provided and was used for all further analysis.

4.3 Bicycle Suitability

As described in Section 2.2, different types of cycling infrastructures are suited for different traffic situations. Bicycle suitability describes cyclists' perceived comfort and safety of a street segment (Lowry et al., 2012). To assess bicycle suitability, measurable factors that influence the route choice of cyclists can be assessed and combined to a score from suitable to non-suitable. The speed limit and the type of infrastructure available on a street segment were combined to a bicycle suitability rating for which a multiplier was defined (see Table 4.1). A slope multiplier was defined and assigned to each street segment depending on the calculated slope (see Table 4.2). The two multipliers were used to calculate the perceived distance for each street segment according to Equation 4.1. The factors were chosen based on available data and were intentionally kept to a minimum. The factors and their cost multipliers were defined following the work of Broach et al. (2012); Grigore et al. (2019); Krenn et al. (2015); Lowry et al. (2016), and Winters et al. (2013).

4.3.1 Suitability Multiplier

Speed limits were used as an approximation for traffic volumes. This is based on the assumption that the traffic calming measures also reduce traffic volumes. In Paris, streets have speed limits of 30 km/h or below in residential streets (e.g. *Zones 30* and *Zones de rencontre*), 50 km/h on larger streets and the main axes, and above 50 km/h on motorways such as the *Péripherique*. Since the motorways have been removed from the data, three speed regimes were relevant for this analysis. The second factor used to describe the bicycle suitability of a street segment was the type of infrastructure provided. There are four main types of infrastructures in Paris that have been described in Section 3.1. For streets with large traffic volumes and high speed limits, cycling infrastructures are necessary. Ideally, the cycling infrastructures should physically separate cyclists from motorized traffic (Paris en Selle, 2018). This corresponds to the infrastructure type *Piste cyclable*. *Bandes cyclables* with painted markings on the street do usually not satisfy cyclists in such traffic situations (Paris en Selle, 2018). Similarly, shared bus lanes (*Couloirs de bus ouverts aux vélos*) do not qualify as suitable cycling infrastructure according to Paris en Selle (2018) since riding on them is considered stressful by many cyclists.

The two factors speed limit and cycling infrastructure were combined to a bicycle suitability rating and a bicycle suitability multiplier as shown in Table 4.1. The multipliers were defined based on the values used in Broach et al. (2012) and Grigore et al. (2019). A multiplier of 1 means that the perceived length is equal to the actual length. A value greater than 1 indicates lacking bicycle suitability: The perceived length of the street segment is longer than its actual length. Values lower than 1 indicate streets suitable for cycling. For speed limits below 30 km/h, a multiplier of 0.8 was defined since traffic volumes are assumed to be particularly low, and riding on these streets should therefore be very safe and comfortable. Streets with a speed limit of 30 km/h are assumed to have low traffic volumes as well and should have good bicycle suitability regardless of the cycling infrastructure provided. Therefore, a multiplier of 1 was assigned to these streets. For streets with a speed limit of 50 km/h, multipliers greater than 1 were defined. Depending on the type of cycling infrastructure provided, these streets were assigned multipliers of 1.1 to 1.4. Streets with speed limits of 50 km/h and no cycling infrastructure received a multiplier of 1.6. In the next step, a bicycle suitability rating (A-E) was assigned to each of the bicycle suitability multipliers according to Table 4.1. The bicycle suitability multipliers and ratings were added to the street data.

Bicycle Suitability Multiplier

Speed Limit	Infrastructure	$M_{Suitability}$	Suitability Rating
-30 km/h	-	A	0.8
30 km/h	-	B	1
50 km/h	Piste cyclable	C	1.1
50 km/h	Double sens cyclable	D	1.4
50 km/h	Couloirs de bus ouverts aux vélos	D	1.4
50 km/h	Bande cyclable	D	1.4
50 km/h	No cycling infrastructure	E	1.6

TABLE 4.1: Bicycle Suitability Multipliers and Bicycle Suitability Ratings.

Since the streets with separated cycling infrastructures (*Pistes cyclables*) are stored as multiple lines in the OSM data (one for the bike lane and one for the street), they have been assigned two different bicycle suitability ratings at this point (A/B and D/E). Since both lines are part of the same street, this needs to be corrected. To do so, the streets with cycling infrastructures of type *Piste uni* (attribute name from the Apur data) that had a street name which had a bicycle suitability rating of D or E were filtered and a bicycle suitability rating C with the corresponding multiplier was assigned to them instead.

The streets were then grouped and their shares on the overall network were calculated in terms of number and length. To identify streets with potential for improvement, the streets of bicycle suitability D and E were analysed more precisely. They were aggregated (sum of lengths of street segments) per street name to create lists with possible improvements.

To explore the results, an empirical evaluation was conducted. This allowed to get a general impression of the different types of cycling infrastructures and the traffic situation in different areas of the city. For each bicycle suitability rating, at least three different streets have been visited and assessed on-site according to the protocol for the empirical evaluation shown in Appendix B.1. The choice of streets did not follow a specific scheme of selection but the streets were located in different parts of the city. Furthermore, the streets that were identified as having the greatest potential for improvement according to the bicycle suitability analysis were observed and evaluated to support the results from the analysis.

4.3.2 Slope Multiplier

The slope was calculated based on a script by RPubs (2018). First, the DEM of the Île-de-France region was cropped to the city boundaries. For each street segment in the cycling data, the highest and the lowest points were flagged. Then, the DEM values of the highest and the lowest point of each line were extracted and the elevation in degrees was calculated for each street segment. Since many of the street segments in the data are only a few meters long, the calculated slopes could be quite steep if a short street segment came to lie on the border of two DEM raster cells with different heights. Also, many streets showed quite steep slopes around the river Seine because its elevation according to the DEM was zero. To correct this effect, all slopes in proximity to the river Seine were set to zero using a buffer of 100 meters around the river.

The slope multipliers were defined based on the studies by Broach et al. (2012) and Grigore et al. (2019) and are listed in Table 4.2. A multiplier of 0 indicates no slope. A value of 0.4 means that cyclists are willing to add 40% of distance to their trip (e.g. 1.4 kilometers instead of 1 kilometer) in order to avoid a slope between 2-4%. Broach et al. (2012) proposed a multiplier of 0.37 for slopes above 2%, 1.2 for slopes above 4% and 3.2 for slopes above 6%. Grigore et al. (2019) used a cost function that produced comparable values as Broach et al. (2012). While Broach et al. (2012) did not include negative slopes, the function by Grigore et al. (2019) considers that steep downhill slopes can also lead to a decrease in safety due to higher cycling speeds. In this study, the network was constructed as an undirected graph meaning that the direction of travel is not considered. Therefore, the same multiplier was assigned for both positive and negative slopes. The multipliers have been defined lower compared to Broach et al. (2012) so that they do not overestimate the effect of slopes. The slope multipliers were added to the data. Values above 0 were added to the previously described bicycle suitability multiplier to create a total multiplier (see Equation 4.1).

Slope Multiplier	
Slope	M_{Slope}
± 0-2 %	0
± 2-4 %	0.4
$\pm > 4\%$	1

Table 4.2: Slope Multipliers.

4.3.3 Perceived Distance

The two multipliers were used to calculate the perceived distance of each street segment as shown in Equation 4.1. The perceived distance of a street segment will be used to calculate the shortest paths between origins and destinations in the next processing step. It allows to roughly model the route choice for cyclists. The total multipliers ($M_{Suitability,s} + M_{Slope,s}$) came to lie between 0.8 and 2.6. A value below one means that the segment is perceived as shorter than its actual distance because of favoring conditions for cycling whereas values above 1 indicate that the street segment is perceived as longer than it actually is. The perceived distance p was calculated as follows:

$$p_s = d_s(M_{Suitability,s} + M_{Slope,s}) \tag{4.1}$$

where d is the distance [m], $M_{Suitability}$ is the bicycle suitability multiplier and M_{Slope} is the slope multiplier of street segment $s \in S$.

4.4 Bikeability

Bikeability can be described as the ability and perceived comfort and safety to access important destinations (Lowry et al., 2012). Bikeability was assessed for the entire case study area using a gravity-based accessibility measure. Different types of destinations and the previously calculated perceived distances were considered.

4.4.1 Network and Routing

First, the street data was converted into an undirected network of class tblgraph (igraph object) based on the code by Van der Meer et al. (2019). The network was then decomposed into its subgraphs and only the main graph (with one graph component) was kept. In this connected graph, there is a connection from all nodes to all other nodes. The network graph contains a geometry list column for both its edges and nodes and allows to apply network measures of the tidygraph package (based on igraph) (Van der Meer et al., 2019). With the creation of the connected graph, 190 street segments (from the original 25'387) were dropped. The created network consists of 25'197 edges and 17'073 nodes.

Two functions were implemented using the igraph package: One calculates the shortest path based on the distances of the edges, the other calculated the perceived shortest path based on the perceived distances of the edges. The functions were used to calculate and compare the shortest path and the perceived shortest path of several exemplary origins and destinations. The function uses the Dijkstra algorithm for the shortest path calculation (Van der Meer et al., 2019). To test whether this simple routing algorithm can roughly model the route choice of cyclists, some exemplary routes were also compared to online routing applications. For the further analysis, it was assumed that cyclists minimize the perceived distance between origin and destination.

4.4.2 Origins and Destinations

In this project, bikeability was calculated per raster cell. A raster template was created for the case study area using the raster package. The package supports raster data in R and provides a set of functions to create, read, export, manipulate and process raster data (Lovelace et al., 2019). The raster template consists of 1'824 raster cells of 250 x 250 meters. It was created based on the extent of the cycling data and thus covers the rectangular bounding box of the cycling data. The raster template was then cropped and masked using the cycling data. By doing so, the raster is cropped to the borders of the cycling data and NA values are assigned to the remaining raster cells. Because the cycling data was used for this step, raster cells that do not contain any street infrastructures (e.g. in the river area and in larger parks) were also assigned NA values. In the raster template, 1'430 out of 1'824 raster cells have street infrastructures on them and are thus relevant for the following analysis.

In the next step, a cell center node needed to be defined for each raster cell. First, the centrality degree was calculated for each node. The corresponding function in R counts the number of edges that are connected to a node. For each raster cell, the node with the highest centrality degree was extracted. The nodes with the highest centrality degree in their raster cell (between 1 and 11) were then filtered. More than one node per raster cell might have the same (highest) centrality degree. For these cases, a function that selects the node closest to the cell centroid was created (code based on Github (2019)). A similar function was also applied for cells that contain no nodes but only edges passing through them. For these cells, the nearest node with the highest centrality degree from a neighboring raster cell was chosen. After these steps, each raster cell had a corresponding cell center node: The node of the network with the highest degree centrality in that (or a neighboring) raster cell that lies closest to the cell centroid. The cell center nodes served as origins and destinations in the analysis.

An origin-destination matrix (with 1'430 origins x 1'430 destinations = ~2 million origin-destination pairs) was created. At this point, it is assumed that trips might take place between one raster cell and all other raster cells. Then, the euclidean distance was calculated for all entries of the matrix and a threshold distance of 4 kilometers was introduced. The origin-destination matrix was filtered for entries below 4 kilometers which resulted in an origin-destination matrix with ~800'000 origin-destination pairs. To reduce processing times, the calculations were carried out on an external server using an SSH (Secure Shell) instance. The origins and destinations are points (the cell center nodes) that represent raster cells of 250 x 250 meters.

To model the number of destinations per raster cell, a destination data set was created from OSM data. The two OSM layers *points of interest* and *transport* were filtered according to Table 4.3 to reflect different types of destinations. Using the raster template, the destinations were counted per raster cell and saved in a destination raster (one for each type of destination and one for the total of destinations). In an effort to avoid cells being overestimated in the bikeability assessment, the maximum count of destinations was set to 10 for the total of destinations, for the destinations of type leisure a threshold of 8 was chosen, 5 for city functions, and 6 for shopping. Also, the number of destinations was calculated and saved for each type of destination.

Types of Destinations

Destination Type	OSM Tags
Leisure	restaurant, fast_food, cafe, bar, pub, attraction, theatre, playground, sports_center, museum, communitycentre, nightclub, food_court, park
Education	school, college, kindergarten, university
City Functions	hospital, pharmacy, bank, laundry, doctors, post_office, library, car_sharing, hairdresser
Shopping	clothes, bakery, convenience, supermarket, bookshop, butcher, shoe_shop, garden_centre, department_store, mall, outdoor_shop, bicycle_shop, kiosk
Public Transport	railway_station

Table 4.3: The types of destinations. The points of interest and the transport layer from OSM were filtered according to this table.

4.4.3 Calculate Bikeability

Bikeability was calculate based on the concept of accessibility introduced in Section 2.5. The perceived shortest path was calculated for each entry of the origin-destination matrix (∼800’000 entries). This step was also carried out using an SSH instance which allowed to reduce processing times. Bikeability was calculated for each origin cell i as the average of perceived shortest paths to all destination cells j weighted and normalized by the number of destinations as shown in Equation 4.2. This approach is similar to studies by Lowry et al. (2012) and Grigore et al. (2019). It combines the destination data with the previously calculated perceived shortest distances and aggregates the values per raster cell.

$$b_i = \frac{\sum_{j \in D}(d_j \times e^{-\beta * p_{ij}})}{\sum_{j \in D} d_j} \tag{4.2}$$

where b_i is the bikeability for raster cell i, d_j is the number of destinations in raster cell j, and p_{ij} is the length of the perceived shortest path [m] between the center node of cell i and the destination center node of cell j. By normalizing by the number of destinations, their influence on the calculation is eliminated. By using an impedance function, closer destinations are valued higher than farther away ones. The beta value of 0.001 was chosen so that the mean bikeability equals 0.5. Bikeability was illustrated on a continuous scale from *Bad Bikeability* to *Good Bikeability* for each type of destination and the total of destinations.

Chapter 5

Results

This chapter outlines the results of the project in three sections. The created cycling data is explored in Section 5.1. The results of the bicycle suitability analysis are shown and explained in Section 5.2 (RQ1). They are completed with observations from the empirical evaluation. Section 5.3 presents the results of the bikeability analysis (RQ2).

5.1 Data Exploration

The cycling data holds 25'387 street segments. The shortest street segment is less than one meter long, the longest has a length of 938 meters. The mean length of all street segments is 66 meters and their median length is 47 meters. 77% of all street segments are less than 100 meters long. 12'093 (roughly 48%) of all street segments have cycling infrastructures on them. The total length of all street segments is 1'682 kilometers, 834 kilometers (roughly 50%) of them provide cycling infrastructures.

Figure 5.1 shows the count of street segments per type of cycling infrastructure and speed limit. Only the ∼12'000 street segments that have cycling infrastructures on them are included in the plot. The most common type of cycling infrastructure in Paris is the *Double sens cyclable*. It is usually installed on one-way streets with a speed limit of 30 km/h or below. The *Pistes cyclables* are cycling infrastructures separated from motorized traffic. Most of them are installed on streets with a speed limit of below 30 km/h. This is because in OSM they are usually stored as separate lines running parallel to the street they are part of which often has a speed limit of 50 km/h. *Bandes cyclables* can be found on streets of all speed limits, *Couloirs de bus ouverts aux vélos* are mostly installed on streets with a speed limit of 50 km/h. Almost 70% of all street segments have a speed limit of 30 km/h or below.

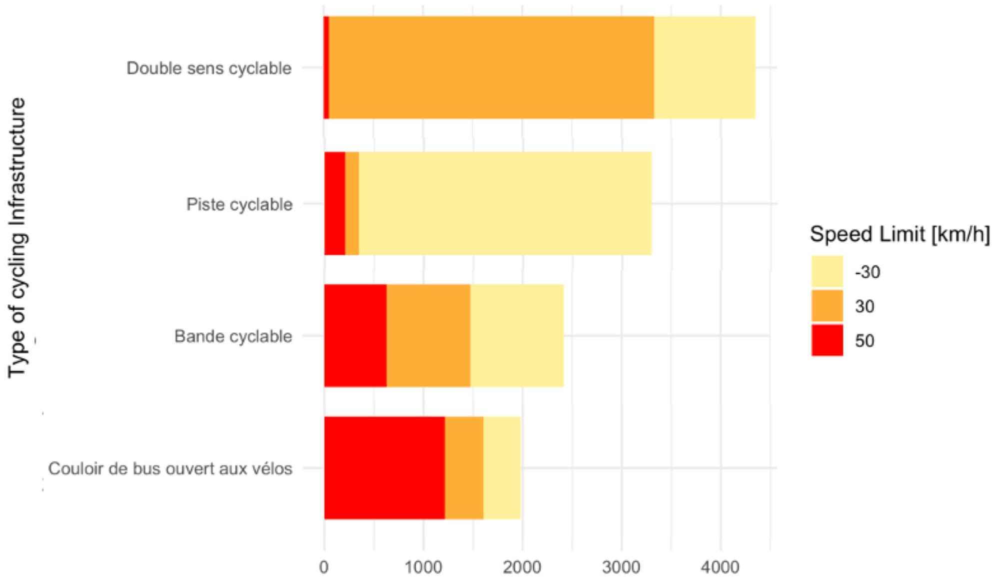
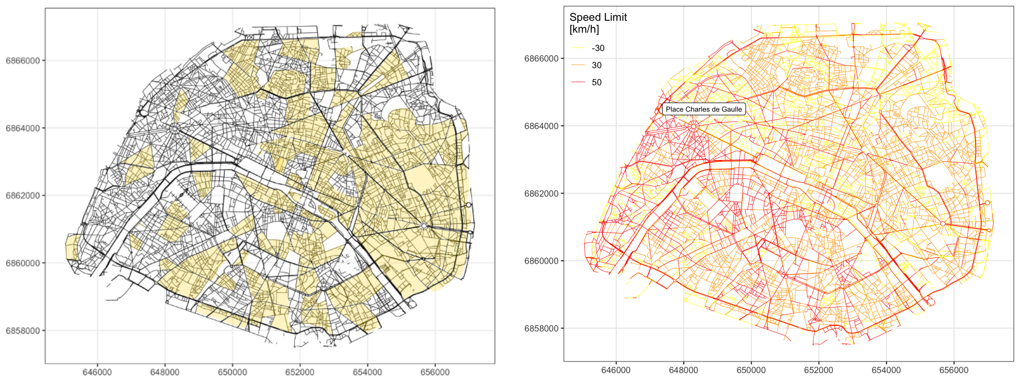


Figure 5.1: The number of street segments per type of cycling infrastructure and speed limit. Only includes street segments with cycling infrastructures.

5.2 Bicycle Suitability

For the bicycle suitability analysis, the speed limit and the type of infrastructure were combined to a bicycle suitability rating for each street segment. The street segments were rated from A (suitable for cycling) to E (not suitable for cycling).

Figure 5.2 shows the *Zones 30* (a) and the speed limits of all street segments (b) in the city of Paris. Speed limits of 30 km/h and below are usually located in the *Zones 30*. Along the river Seine, on the main axes (three main rings around the center), and in areas that have not yet been transferred to *Zones 30*, there are streets with a speed limit of 50 km/h. In the west of the city and especially in the area south of *Place Charles de Gaulle* several areas have not yet been transformed into *Zones 30*.

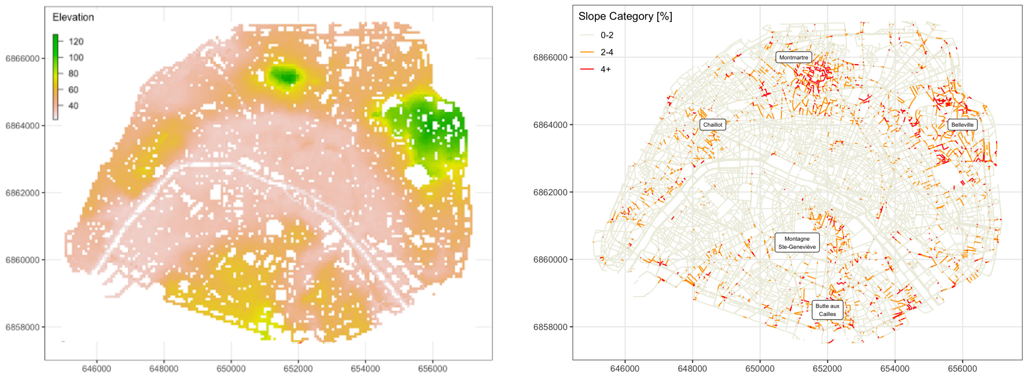


(a)

(b)

Figure 5.2: The *Zones 30* (a) and the different speed limits (b) in the city of Paris.

Figure 5.3 shows the Digital Elevation Model (a) and the calculated slopes of all street segments (b) in the city of Paris. The steepest slopes can be found around the hill of *Montmartre* in the north of the city on which the *Basilique du Sacré-Cœur* is situated, and around the hill of *Belleville* to the northeast. The map also shows smaller elevations such as *Butte aux Cailles*, *Chaillot*, and the *Montagne Sainte-Geneviève* on which the *Panthéon* is located. The map shows both positive and negative slopes in degrees (e.g. a street segment with an elevation change of 6 meters over 100 meters has a slope of 6%). 88% of all street segments do not have a slope according to the calculations. Roughly 1’800 street segments (7%) have a slope between 2-4% and roughly 1’200 street segments (5%) have a slope greater than 4%.



(a)

(b)

Figure 5.3: The Digital Elevation Model (a) and the different slope categories (b) in the city of Paris.

The results of the bicycle suitability analysis are illustrated in Figure 5.4. Table 5.1 shows the share of street segments that have been assigned to each of the bicycle suitability ratings (number and length). Half of the street segments have a rating of A or B, which means that the speed limit is 30 km/h or below, and are thus suitable for cycling. A bicycle suitability rating C corresponds to a speed limit of 50 km/h with cycling infrastructures of type *Piste cyclable*. These streets segments are also suitable for cycling because cyclists are separated from motorized traffic. 30% of all street segments were rated with a bicycle suitability C. Street segments with a speed limit of 50 km/h and another type of cycling infrastructure (*Double sens cyclable*, *Bande cyclable* or *Couloir de bus ouvert aux vélos*) were rated with a bicycle suitability D. This concerned 8% of all street segments. The remaining 12% of street segments have a speed limit of 50 km/h and no cycling infrastructure and were therefore rated with bicycle suitability E. In areas that have not yet been transformed to *Zones 30* (see Figure 5.2), there is a high concentration of street segments with bicycle suitability of E, even in residential areas. Clusters can be identified south of the *Place Charles de Gaulle* on which the *Arc de Triomphe* is located, around the *Hôtel des Invalides*, and in the district *Auteuil* in the south-west of the city.

FIGURE 5.4: Bicycle suitability of street segments in the city of Paris.

Bicycle Suitability					
	A	B	C	D	E
Number of segments	4562	8027	7743	1896	3159
% of segments	18	32	30	8	12
Length (km)	305	612	447	120	199
% of length	18	36	27	7	12

TABLE 5.1: Number of street segments and length of street segments per bicycle suitability rating.

Since the bicycle suitability assessment is ultimately most meaningful on a street level, further exploration of the results asks for a different scale. One option is to have a closer look at streets with bicycle suitability ratings of C, D, and E. Lists were created for each of these bicycle suitability ratings by aggregating (sum) the lengths of street segments per street name. Since a street might have several types of cycling infrastructures and thus different suitability ratings assigned to it, it might appear on multiple lists. Tables 5.2, 5.3, and 5.4 list the 10 longest streets with bicycle suitability ratings C, D, and E. All the listed streets are illustrated in Figure 5.5. The latter two tables for bicycle suitability ratings D and E specifically identify potential locations for improvement of cycling infrastructures. The tables also describe the current situation of the streets based on the results of the analysis, the objectives of the *Plan Vélo 2015-2020*, the assessment by the Observatoire du Plan Vélo (2020), and the empirical evaluation. An extended list of the 50 longest streets of bicycle suitability D and E (grouped by street name and sorted by length) can be found in Appendices C.1 and C.2. The Appendices additionally indicate the length of each street with potential for improvement.

Many of the streets with a bicycle suitability C are part of the express network or the structuring network of the *Plan Vélo 2015-2020* (see Figure 3.2) on which the goal was to provide separated cycling infrastructures (La Ville de Paris, 2021; Mairie de Paris, 2015). The results suggest that such infrastructures are provided on many of Paris' major street axes. Table 5.2 lists the 10 longest streets with bicycle suitability C. Some of the listed streets (*Voie Georges Pompidou, Rue de Rivoli*, and *Quai de Bercy*) are part of the express network projected in the cycling plan. Other streets from the list are part of the structuring network, the three rings around the city, according to the cycling plan (*Boulevard St-Germain, Boulevard Davout, Boulevard Sérurier* and *Boulevard Brune*). The latter three had already been installed previous to the cycling plan. *Boulevard St-Germain* has a bicycle suitability C according to the analysis but the Observatoire du Plan Vélo (2020) considers it as non-satisfactory. The empirical evaluation showed that there are shared bus lanes provided on parts of the street but they are not continuous and only allow for cycling in one direction of travel. The remaining three streets from Table 5.2 (*Avenue Jean Jaurès, Boulevard Voltaire* and *Boulevard de Magenta*) are part of the secondary network according to the cycling plan. The cycling infrastructures on the latter two streets have been installed within the plan duration, on *Avenue Jean Jaurès* they have been installed before the cycling plan.

Figure 5.5: The 10 longest streets with bicycle suitability C, D, and E. These streets are listed in Tables 5.2, 5.3, and 5.4.

The streets that were rated with a bicycle suitability D have cycling infrastructures on them that might not provide sufficient comfort and safety to cyclists. Therefore, there is potential for improvement of cycling infrastructures on these streets. Streets with *Bandes cyclables* might feel dangerous for cyclists because they are not physically separated from motorized traffic. Streets with *Couloirs de bus ouverts aux vélos* are usually wide and thus comfortable for cycling but buses and taxis can pass cyclists with high speeds which might be perceived as unsafe. Also, these infrastructures are sometimes only provided in one direction of travel leaving cyclists traveling the other direction without cycling infrastructures. Table 5.3 lists the 10 longest streets with bicycle suitability D. Based on the results and the empirical evaluation, the most potential for improvement in this bicycle suitability rating is on streets with infrastructures of type *Bande cyclable* (*Boulevard Malesherbes* and *Boulevard Exelmans*) and streets with one-directional shared bus lanes (*Rue de Vaugirard* and *Avenue de Versailles*).

Cycling infrastructures of type *Couloirs de bus ouverts aux vélos* that run in both directions (*Boulevard Raspail, Avenue du Président Wilson, Avenue du Président Kennedy*) have been perceived as comfortable for cycling in the empirical evaluation. The cycling infrastructures on some of the listed streets have recently been improved or are currently being improved (*Avenue de Flandre, Rue Lecourbe* and *Avenue de New York*). In this bicycle suitability rating, the importance of continuous infrastructures is especially noticeable. Different types of cycling infrastructures on a street can be confusing for cyclists, especially when they are not well indicated.

Table 5.4 shows the 10 longest streets with a bicycle suitability rating E. On these streets with a speed limit of 50 km/h, no cycling infrastructure is provided. The situation on some of these streets has already been improved (*Avenue Foch, Avenue du Maine* and *Boulevard du Montparnasse*) or are currently being improved (*Boulevard Haussmann* and *Avenue de la République*). However, according to the empirical evaluation, the situation on these streets is not satisfying (except for *Boulevard du Montparnasse*) because the type of cycling infrastructure is not suitable or because they are not continuous. For the *Avenue du Maine* and *Boulevard Haussmann* this obervation is supported by the Observatoire du Plan Vélo (2020). On the remaining streets from the list (*Boulevard Pereire, Avenue de Breteuil, Avenue Victor Hugo, Rue du Faubourg Saint-Honoré*, and *Rue de Vaugirard*) there are no cycling infrastructures provided over long stretches of the street.

The exploration of the results shows that each street needs to be examined individually. Not all streets with the same bicycle suitability rating provide the same comfort and safety for cyclists. Furthermore, some of the examples show that the situation for cyclists can change quite rapidly which confirms that the efforts by the city to improve cycling infrastructures are noticeable. Some of the recent improvements are represented in the data, some of them could be observed in the course of the empirical evaluation.

The 10 longest streets with bicycle suitability C	
Street	Situation
Bd Voltaire	Projected in the cycling plan (secondary network) and installed since. Separated but rather narrow cycling infrastructures on both sides of the street. Generally continuous and well visible at intersections, satisfying according to Observatoire du Plan Vélo (2020).
Voie Georges Pompidou	Projected in the cycling plan (express network) and installed since. Part of the express network along the Seine. A mix of wide separated cycling lanes on both sides of the street, shared bus lanes, and bidirectional separated cycling infrastructures. According to Observatoire du Plan Vélo (2020), the cycling tunnels are closed at night and many pedestrians use the shared spaces making cycling difficult at times.
Rue de Rivoli	Projected in the cycling plan (express network) and installed since. Part of the express network. Separated cycling infrastructures on two entire lanes of the street. Very little motorized traffic is allowed on the remaining lane.
Quai de Bercy	Projected in the cycling plan (express network) and installed since. Part of the express network along the Seine. Wide separated cycling lane along the river Seine, sometimes shared with pedestrians.
Bd Davout	Already in place before cycling plan (structuring network). Bidirectional cycling lane on one side of the street. Generally continuous and well visible at intersections.
Bd Sérurier	Already in place before cycling plan (structuring network). Bidirectional cycling lane on one side of the street. Generally continuous and well visible at intersections.
Av. Jean Jaurès	Already in place before cycling plan (secondary network). Separated but rather narrow cycling infrastructures on both sides of the street. Generally continuous and well visible at intersections.
Bd Saint-Germain	Projected in cycling plan (structuring network) and partly installed since. Sometimes shared bus lanes. Cycling infrastructures not satisfying according to Observatoire du Plan Vélo (2020).
Bd de Magenta	Projected in the cycling plan (secondary network) and installed since. Separated but rather narrow cycling infrastructures on both sides of the street. Generally continuous and well visible at intersections. According to Observatoire du Plan Vélo (2020) many pedestrians are walking on the cycling infrastructures making cycling difficult at times.
Bd Brune	Already in place before cycling plan (structuring network). Separated but rather narrow cycling infrastructures on both sides of the street. Generally continuous and well visible at intersections.

TABLE 5.2: The 10 longest streets with bicycle suitability C. On these streets, infrastructures that physically separate cyclists from motorized traffic are provided according to the bicycle suitability analysis.

The 10 longest streets with bicycle suitability D	
Street	Situation
Bd Raspail	Cycling infrastructure of type *Couloir de bus ouvert aux vélos* is installed on most parts of the street. Wide lane shared with buses and taxis. Completed according to cycling plan (secondary network).
Av. de Flandre	Projected in the cycling plan (secondary network) and installed since. Separated but rather narrow cycling infrastructures along the pedestrian island in the middle of the street. Traffic needs to be crossed to reach the cycling infrastructures. Satisfying according to Observatoire du Plan Vélo (2020).
Bd Malesherbes	Cycling infrastructure of type *Bande cyclable* is installed on most parts of the street in both directions. Completed according to cycling plan (secondary network).
Rue de Vaugirard	Cycling infrastructure of type *Couloir de bus ouvert aux vélos* and *Bande cyclable* installed on parts of the street. Not continuous and often only in one direction of travel. Completed according to cycling plan (secondary network).
Rue Lecourbe	Projected in the cycling plan (secondary network) and installed since. Separated but rather narrow cycling infrastructures against the general direction of traffic and *Bande cyclable* in the direction of traffic. Satisfying according to Observatoire du Plan Vélo (2020).
Bd Exelmans	Cycling infrastructure of type *Bande cyclable* installed on most parts of the street in both directions. Completed according to cycling plan (structuring network).
Av. du Président Wilson	Cycling infrastructure of type *Couloir de bus ouvert aux vélos* installed on most parts of the street. Wide lane shared with buses and taxis. Completed according to cycling plan (secondary network).
Av. du Président Kennedy	Cycling infrastructure of type *Couloir de bus ouvert aux vélos* installed on most parts of the street. Wide lane shared with buses and taxis. Completed according to cycling plan (secondary network).
Av. de New York	Cycling infrastructure of type *Bande cyclable* and *Couloir de bus ouvert aux vélos* installed on parts of the street in both directions. Projected in the cycling plan (express network), not satisfying according to Observatoire du Plan Vélo (2020). Cycling infrastructures are currently being improved.
Av. de Versailles	Projected in the cycling plan (express network). Cycling infrastructure of type *Couloir de bus ouvert aux vélos* installed on parts of one side of the street. Not continuous and often only in one direction of travel.

Table 5.3: The 10 longest streets with bicycle suitability D. These streets have a speed limit of 50 km/h and no infrastructures that physically separates cyclists from motorized traffic according to the bicycle suitability analysis.

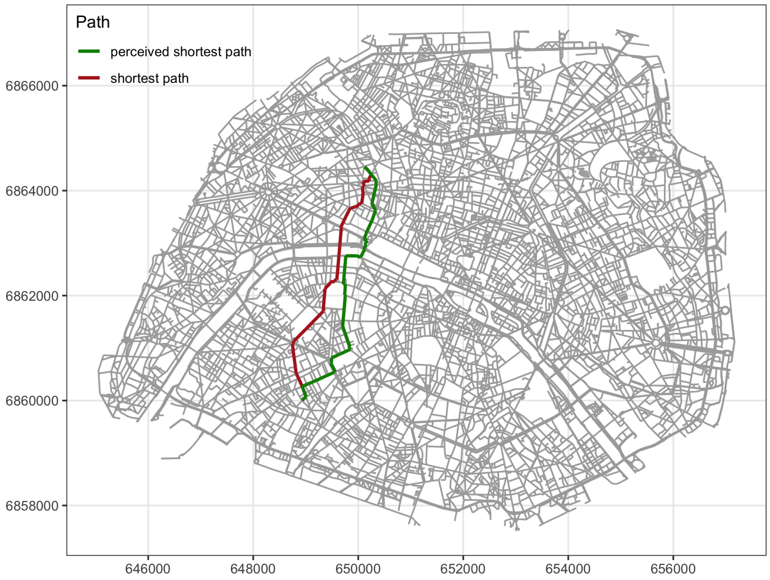
The 10 longest streets with bicycle suitability E	
Street	Situation
Bd Pereire	Rather narrow street with pedestrian island. No cycling infrastructures are provided.
Av. Foch	Cycling infrastructure of type *Bande cyclable* is installed on most parts of the street in both directions. Completed according to cycling plan (secondary network).
Av. du Maine	Cycling infrastructure of type *Couloir de bus ouvert aux vélos* is installed on parts of one side of the street. Not continuous and often only in one direction of travel. Cycling infrastructures not satisfying according to Observatoire du Plan Vélo (2020).
Bd du Montparnasse	Bidirectional *Couloir de bus ouvert aux vélos* in the middle of the road. Traffic needs to be crossed to reach the cycling infrastructures. Wide lanes that allow traveling in both directions. Completed according to cycling plan (secondary network).
Av. de Breteuil	Rather narrow street with pedestrian island. No cycling infrastructures are provided.
Av. Victor Hugo	Bidirectional street with one lane per direction and no cycling infrastructures.
Bd Haussmann	Cycling infrastructure of type *Couloir de bus ouvert aux vélos* is installed on parts of the street. Projected in cycling plan (secondary network), not satisfying according to Observatoire du Plan Vélo (2020). Cycling infrastructures are currently being improved.
Av. de la République	Cycling infrastructure of type *Couloir de bus ouvert aux vélos* and *Piste cyclable* is installed on parts of the street. Projected in cycling plan (secondary network), not satisfying according to Observatoire du Plan Vélo (2020). Cycling infrastructures are currently being improved.
Rue du Faubourg Saint-Honoré	One-directional street with one lane and no cycling infrastructures.
Rue de Vaugirard	Cycling infrastructure of type *Couloir de bus ouvert aux vélos* and *Bande cyclable* is installed on parts of the street. Not continuous and often only in one direction of travel. Completed according to cycling plan (secondary network).

TABLE 5.4: The 10 longest streets with bicycle suitability E. These streets have a speed limit of 50 km/h and do not (or only partially) have any cycling infrastructure according to the bicycle suitability analysis.

5.3 Bikeability

For the bikeability analysis, a network was created from the street segments. The (connected) network consists of 25'197 edges and 17'073 nodes. The calculated perceived distances were used for routing in the network. The implemented function allowed calculating the perceived shortest path between all nodes in the network. The perceived shortest path was compared to shortest paths from online applications for a few exemplary sets of origins and destinations. The route generated by this simple routing algorithm usually deviates from routing applications. However, the routing algorithm can detect streets with lacking bicycle suitability and hills. Figure 5.6 shows two routing examples: Example 1 (a) Roads with lacking bicycle suitability, Example 2 (b) Hill.

The destination raster in Figure 5.7 (a) shows the count of destinations per 250 x 250 meters raster cell. A maximum value of 10 destinations was defined for the total of destinations to avoid cells being overestimated in the bikeability assessment. The destination rasters for the other sets of destinations (leisure, public transport, shopping, education, and city functions) can be found in Appendix D.1 and D.2. Figure 5.7 (a) shows a noticeable concentration of destinations in the center of Paris north of the river Seine and a smaller concentration of destinations south of the river. There are smaller clusters with more than 5 destinations per raster cell in different areas around the city and large areas count 3 or 4 destinations per raster cell. Of course, no destinations are located in the river.



(a)

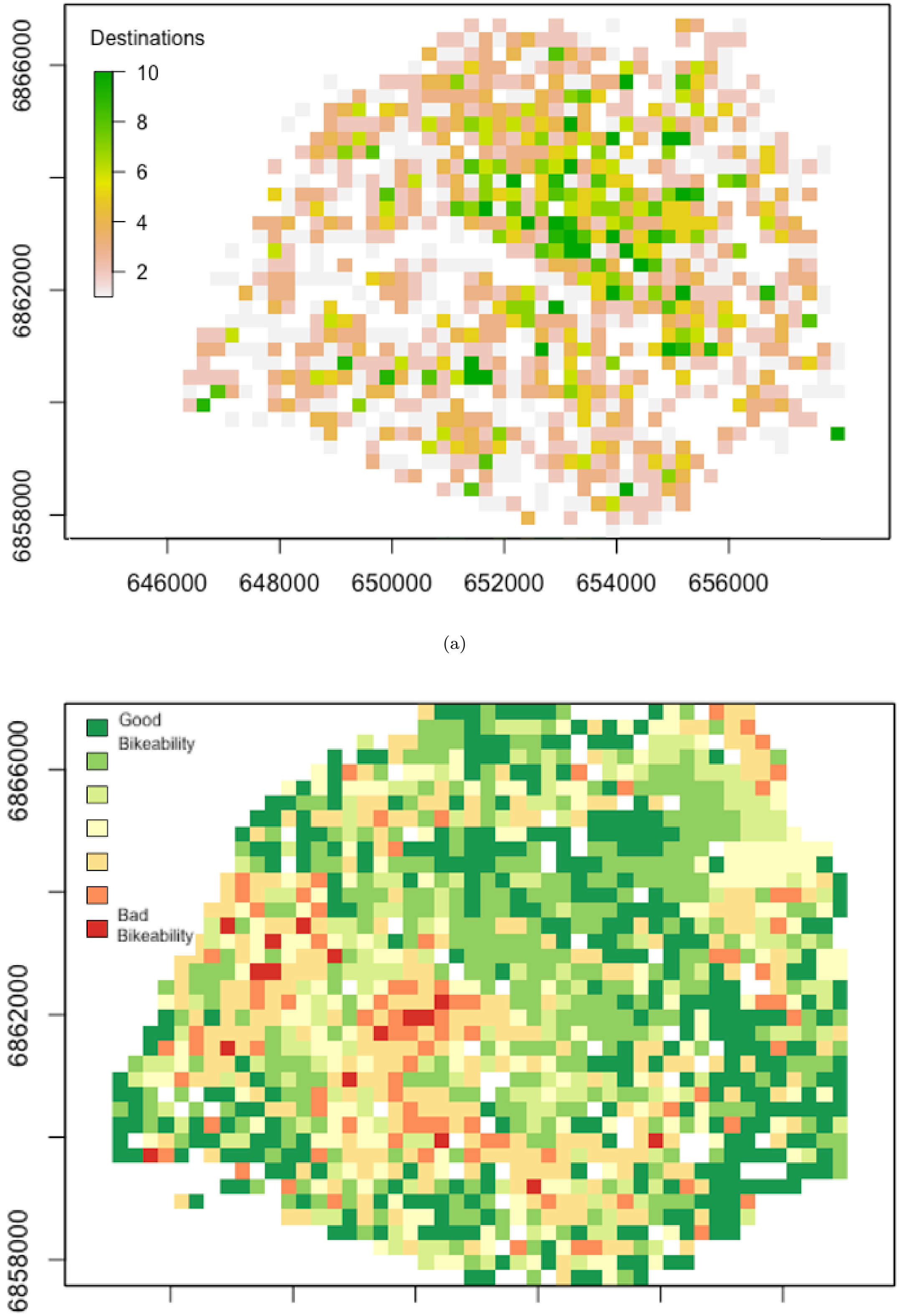
(b)

Figure 5.6: The shortest path and the shortest perceived path for two exemplary routes. Example 1: Streets with lacking bicycle suitability (a) and Example 2: Hill (b).

After defining a cell center node for each raster cell and calculating the perceived shortest path for each pair in the origin-destination matrix, bikeability was calculated for the different sets of destinations according to Section 4.4. Figure 5.7 (b) shows the bikeability in the city of Paris. The bikeability results for the different sets of destinations (leisure, public transport, shopping, education, and city functions) can be found in Appendices D.1 and D.2.

The best bikeability values can be found north of the river in the central city area. This correlates with the density of destinations in that area. This is partly an effect of the applied formula which values destinations closest to the origin node most. South of the river in the city center, there is a cluster of bad bikeability values. This can be explained by the lack of destinations and might also be due to the concentration of streets with lacking bicycle suitability in that area. The same effect can be observed in the area around *Place Charles de Gaulle*, where the bicycle suitability analysis showed a high concentration of street segments with lacking bicycle suitability. Toward the edges of the city, the bikeability values are rather good which indicates that important destinations can also be reached from origins towards the city borders. The comparably bad bikeability values in the northeast of the city can be explained by the fact that there are several raster cells in that areas with no destinations which is not the case for most other areas in proximity to the city borders. The slope might also influence the bikeability values in this area of the city. When comparing different sets of destinations (see Appendices D.1 and D.2) it can be noticed that more evenly distributed destinations (e.g. public transport or education) also show more evenly distributed bikeability values. However, the patterns of the total of destinations shown in Figure 5.7 are reflected in the results of all other sets of destinations as well.

The results of the bikeability analysis reflect to some degree the results from the bicycle suitability analysis. Areas with higher concentrations of street segments with lacking bicycle suitability also tend to have lower bikeability values.



(a)

(b)

FIGURE 5.7: The total of destinations (a) and the bikeability (b) in the city of Paris.

Chapter 6

Discussion

This project aimed to assess where cycling infrastructure could be improved in the case study area of Paris. The proposed methods allowed identifying specific streets and areas of the city where the improvement of cycling infrastructures would be valuable for the overall cycling network. The objective of this chapter is to discuss the research questions outlined in Section 1.2 based on the State of the Art introduced in Chapter 2 and the Results described in Chapter 5. The two research questions are discussed in Sections 6.1 and 6.2. In Section 6.3, overall limitations such as the data availability and the model design are discussed. While the discussion aims to answer the research questions, the focus is on reflecting the limitations of the chosen approach and its implications on literature.

6.1 Bicycle Suitability

RQ1: Where lie the potentials for improvement of cycling infrastructures that increase the bicycle suitability in the city of Paris?

The assessment of bicycle suitability revealed for each street segment how suitable it is for cycling (from A to E). The assessment specifically addresses the first research question of this project and has allowed identifying potential locations for improvement of bicycle infrastructures that increase bicycle suitability in the city of Paris (see results in Section 5.2). The bicycle suitability analysis included two factors: Bicycle infrastructure and speed limit. The factors reflect the two most important approaches to make cycling safe and convenient suggested by Pucher and Buehler (2008): (1) The provision of separate cycling facilities along streets with heavy traffic and at intersections and (2) extensive traffic calming of residential neighborhoods.

Since speed limit has been used as an approximation for traffic volumes due to data limitations, the *Zones 30* in Paris play into both approaches by Pucher and Buehler (2008). The assumption that traffic volumes are low when speed limits are reduced is only realistic where extensive and effective traffic calming policies are put into place. While there certainly is a correlation between these two factors, no reliable sources could be found that suggest using them interchangeably. To what degree the city of Paris succeeds with traffic calming measures is not analysed in this project. In the empirical evaluation, the *Zones 30* have been observed to have rather low amounts of traffic. They have generally been perceived as safe and comfortable for cycling. However, it can be difficult for cyclists when there are comparably high traffic volumes, even if speed limits are low. Such situations have been observed on a few occasions. Also, riding in narrow one-way streets against motorized traffic can be a stressful experience.

Two further aspects that could not be considered in this analysis are the condition (e.g. surface quality) and layout (e.g. width) of the provided cycling infrastructures. This is an important limitation because it has been found that many of the perceived problems with cycling are due to inadequate design or maintenance rather than the type of cycling infrastructure (Parkin and Koorey, 2009). The pure existence of cycling infrastructure does not automatically lead to a perfect situation for cyclists - their condition, the availability of bike parking, and traffic guidance need to be considered as well (Pucher et al., 2010). This complexity is also reflected in the design principles for cycling infrastructures by CROW (2007): Safety, directness, comfort, coherence, and attractiveness.

In this project, 50% of all street segments (54 % of the total length of all street segments) were rated as A or B in terms of bicycle suitability. These streets are mostly located in *Zones 30* and can be considered safe and comfortable for cyclists to ride on. Similarly, Lowry et al. (2012) found that a majority of the local streets in Moscow, USA, exhibit a good BLOS and thus provide good conditions for cycling. However, Lowry et al. (2012) do not indicate the share of streets this corresponds to or what policies the city has put in place to ensure safe and comfortable conditions for cyclists in these areas. Grigore et al. (2019) assessed cycling infrastructures in a district of Basel, Switzerland,

and found that the cycling infrastructures in residential areas of Basel are generally very well suited for cycling. Therefore, the results of this analysis support the above-mentioned findings: Streets in residential areas (here often in *Zones 30*) are suitable for cycling and important to the overall cycling network if traffic calming measures are in place.

Another 30% of all street segments (27% of their length) fell into category C in terms of bicycle suitability. Given the strong consensus in literature that physically separated cycling infrastructures are an important measure along streets with heavy traffic to make cycling safe and convenient (Dill and Mcneil, 2013; Larsen and El-Geneidy, 2011; Pucher and Buehler, 2008), these streets can be considered suitable for cycling. The proposed method allows locating streets with separated cycling lanes. More importantly, however, the method can be used to identify street segments with potential locations for improvement in terms of bicycle suitability (rating D or E). In this analysis, this concerns 20% of all street segments with 19% of their length. Cycling on these streets can be perceived as stressful and unsafe. It is assumed that cycling infrastructures on street segments of rating D or E would need to be improved so that they thereafter fall into ratings A-C. Since it is mostly the main axes of the street network that fall into categories C-E, these types of streets show the biggest variation in terms of bicycle suitability. Similarly, both Lowry et al. (2012) and Rybarczyka and Wu (2010) found that collector (and arterial) streets exhibit the most variation in BLOS compared to other types of streets. Similar to BLOS grades, the proposed bicycle suitability classification often complies with road types (Rybarczyka and Wu, 2010). Compared to BLOS assessments, the chosen approach is simpler in its design, requires fewer different data sources, and yet leads to comprehensive results. Spatially, the road segments with lower bicycle suitability are evenly distributed in the study area with a noticeable cluster in the northwest of the city around *Place Charles de Gaulle*. In short, the proposed method can identify precisely which street segments have potential for improvement in terms of bicycle suitability and what type of cycling infrastructure is currently provided on them (in the case of category D).

The results of the analysis show important similarities with the *Plan Vélo 2015-2020*. The similarities with the cycling plan indicate that the proposed method could be used as a tool for network evaluation and development. The following list shows a few manifestations of this finding:

- Streets with bicycle suitability C that were projected lines in the cycling plan: These infrastructures have been installed as planned. For example: *Boulevard Voltaire, Voie Georges Pompidou, Rue de Rivoli*, and *Quai de Bercy.*
- Streets that were projected lines in the cycling plan and have been improved after the data collection: These infrastructures have received a bicycle suitability ranking in the analysis that does not represent the current state of the street according to the empirical evaluation and the assessment by the Observatoire du Plan Vélo (2020). For example: *Avenue de Flandre* and *Rue Lecourbe.*
- Streets that are part of the list with potential for improvement and were projected in the cycling plan: These infrastructures have not yet been installed according to the analysis. The results of the analysis are confirmed by the Observatoire du Plan Vélo (2020). For example: *Avenue du Maine, Boulevard Haussmann* and *Avenue de la République.*
- Streets that are part of the list with potential for improvement but were not projected in the cycling plan: The results suggest that there is potential for additional cycling infrastructures on these streets. For example: *Boulevard Pereire, Avenue de Breteuil, Avenue Victor Hugo* and *Rue du Faubourg Saint-Honoré.*
- Streets that are part of the list with potential for improvement and marked as existing cycling infrastructures in the cycling plan. The results suggest that the cycling infrastructures on these streets might be unsuitable for cycling. For example: *Boulevard Raspail, Boulevard Malesherbes, Boulevard Exelmans, Avenue du Président Wilson, Avenue du Président Kennedy, Avenue Foch, Boulevard du Montparnasse* and *Rue de Vaugirard.*

The proposed method can precisely identify locations with potential for improvement of cycling infrastructures that increase bicycle suitability and can therefore be used as a tool for cycling network evaluation and development. Potential measures on streets that have been identified in this analysis need to be examined individually and further assessed in the context of the overall cycling network.

Key messages:

- The proposed method allows identifying street segments with potential for improvement in terms of bicycle suitability.
- The results show important similarities with the *Plan Vélo 2015-2020* which indicates that the proposed method could be used as a tool for network evaluation and development.
- The effect of traffic calming measures was not assessed in this work. Furthermore, no conclusions can be drawn in terms of the design and maintenance of the provided bicycle infrastructures.
- The identified street segments need to be further assessed individually and examined in the context of the overall cycling network.

6.2 Bikeability

RQ2: How do the potentials change when considering bikeability?

The bikeability assessment shows for each origin zone the convenience and comfort of reaching destinations by bicycle (rating from *Bad Bikeability* to *Good Bikeability*). The proposed method takes into account the perceived distances on the route between the origins and the destinations. The approach addresses the second research question of this project. The results described in Section 5.3 are discussed in this section.

In this project, the perceived distance was calculated to reflect the travel impedance on the route between origins and destinations. The shortest paths were calculated based on the length of the street segments, the bicycle suitability (bicycle suitability multiplier), and the slope (slope multiplier). Two further factors that strongly influence the route choice of cyclists, intersections and traffic volumes, could not be considered in this project due to data limitations. Intersections are an important source of accidents, conflict, and delay for cyclists (Broach et al., 2012; Dill and Mcneil, 2013; Grigore et al., 2019), traffic volumes strongly influence their perceived comfort and safety (Broach et al., 2012; Hood et al., 2011; Sener et al., 2009). Therefore, it would have been interesting to include these two factors in the analysis to model the travel behavior of cyclists more precisely. For example, the intersections could be included by assessing their suitability for cycling as done in Grigore et al. (2019); Lowry et al. (2016) and Mekuria et al. (2012), by considering the number of intersections on a route or by assuming that more central intersections (e.g. high centrality degree) are avoided by cyclists. Since a goal of this project was to propose a method that only uses commonly available data so that it could be applied to different case study areas, other factors that can influence the route choice of cyclists were not considered.

Using perceived distances to calculate the shortest routes follows the examples of Grigore et al. (2019); Klobucar and Fricker (2007) and Lowry et al. (2012). The approach can be considered an alternative to more sophisticated and detailed route choice models that include additional factors or use travel behavior data (such as GPS tracking data). The accuracy of the proposed routing algorithm functions was only verified qualitatively for some exemplary origins and destinations. In the samples that were tested, hills and streets with lacking cycling infrastructures could be detected. Therefore, it is assumed that a majority of cyclists' preferences could be captured. This suggests that bicycle suitability multipliers between 0.8 (bicycle suitability rating A) and 1.6 (bicycle suitability rating E) are appropriate to reflect the effect of suitable bicycle infrastructure on a given street and validates the multipliers used by Broach et al. (2012) and Grigore et al. (2019). The results show that even with a lower slope multiplier than the one proposed by Broach et al. (2012), hills could be detected. This implies that their values might overestimate the effect of slopes. The analysis confirms that it is possible to create a basic routing algorithm based on a small number of factors that can roughly model the route choice of cyclists. Of course, more precise routing models might be needed depending on the purpose of the analysis.

Bikeability was calculated per raster cell. For many aspects of transport system modeling, it makes sense to start with areal data such as origin zones and destination zones, even though the network itself consists of lines and nodes (Hollander, 2016). While the zones do little justice to the detailed nature of bicycle travel (Iacono et al., 2010), they help to break down continuous space into tangible units (Hollander, 2016). The same geographic units were used for origins and destinations, which is often the case in transport research (Lovelace et al., 2019). The reviewed literature either uses administrative zones such as residential parcels or traffic analysis zones (e.g. in Lowry et al. (2016);

Mekuria et al. (2012); Saghapour et al. (2017)) or raster cells (e.g. in Grigore et al. (2019); Grisé and El-Geneidy (2018); Iacono et al. (2010); Krenn et al. (2015); Larsen et al. (2013); Lowry et al. (2012); Winters et al. (2013)) as a basis. A major advantage of raster cells is the simplicity with which various factors from different data sources can be incorporated (especially valuable in multi-criteria analysis approaches) and that the results are easy to interpret (Larsen et al., 2013). For the case study area, there are some administrative zones such as the 80 districts or analysis zones defined by Apur (2020) that could have been used for this analysis. Nevertheless, raster cells were chosen to capture bikeability in this project to ensure good interpretability and transferability to other case study areas.

The resolution of the raster cells also needs to be considered: Small zones are preferable since they lead to more refined results (Hollander, 2016). However, their high number can have consequences for processing times: In an origin-destination analysis, the number of possibilities increases as a non-linear function of the number of zones (Hollander, 2016). In this work, raster cells of 250 x 250 meters were chosen. There are examples of studies that use smaller (e.g. Grigore et al. (2019); Krenn et al. (2015); Terh and Cao (2018); Winters et al. (2013)) or larger (e.g. Grisé and El-Geneidy (2018); Larsen et al. (2013)) raster cells. While smaller cell sizes would have led to more precise results, the processing time would not have been manageable. A compromise would have been to compute bikeability only for a part of the city as e.g. Grigore et al. (2019) and Terh and Cao (2018) did. Since the goal was to assess bikeability for the entire case study area this option was dismissed. In the work by Lowry et al. (2012), the introduction of individual cycling infrastructures in Moscow, USA, was found to have major effects on the bikeability in the surrounding areas. Even when using smaller cell sizes, such strong effects could probably not have been detected in the chosen case study area because the cycling network is more mature in comparison to the one in Lowry et al. (2012) and has far more streets that are suitable for cycling.

The destinations were counted per destination zone as described by Iacono et al. (2010) and Mekuria et al. (2012) - in a sense the activity potential of the zone. Locating all of a zones' destinations at one point per zone (often the centroid) can lead to distortions in results since zones with barriers will have different characteristics in terms of the ability to reach the centroid (Mekuria et al., 2012). To avoid such distortions, the network node with the highest network centrality per raster cell was chosen as the origin and destination node - an approach that has not been observed in other studies.

The careful choice of origins and destinations is important for efficient cycling network planning (Gerike and Jones, 2016). Various studies show that not only employment but also access to other destinations such as retail, recreation, and education can influence travel behavior (Iacono et al., 2010; Saghapour et al., 2017) - the choice of destinations strongly depends on the focus of the study. To better understand the influence of different types of destinations on bikeability, the analysis included different types of destinations. Bikeability was calculated for the five different types of destinations individually: Leisure, education, city functions, shopping, and public transport, and for the total of all destinations. In the case study area, there is a concentration of destinations in the city center north of the river. Some types of destinations are mainly concentrated in this area of the city (most prominently leisure but also shopping and city functions), while other types of destinations are more evenly distributed throughout the city (e.g. public transport and education). Only including more evenly distributed destinations such as public transport stops also results in more evenly distributed bikeability values.

A gravity-based (Hansen-type) accessibility model was applied because such models tend to be suitable for non-motorized travel, can easily be operationalized and are relatively easy to interpret and communicate (Iacono et al., 2010; Saghapour et al., 2017). However, this type of measure also has important limitations. For example, it ignores temporal and individual components of accessibility (Iacono et al., 2010). Furthermore, Iacono et al. (2010) point out that intrazonal trips remain unconsidered with this type of accessibility measure. However, according to Mekuria et al. (2012), intrazonal trips do not have an important effect in such analyses since walking is more convenient than cycling for very short distances. Since cycling trips don't usually cover long distances either, a maximal threshold has been defined for the cycling trips following the example of Lowry et al. (2016) and Saghapour et al. (2017). Defining the maximal acceptable distance for bicycle use is not trivial and there is a risk to exclude too many potential destinations from the analysis by doing so (Saghapour et al., 2017). Saghapour et al. (2017) calculated a separate origin-destination matrix for each type of destination using a different threshold (e.g higher threshold for education centers than for retail destinations). The proposed method is simpler in its design and allows to include or exclude destinations with very little effort while still including different types of destinations. In this work, origin-destination pairs with a euclidean distance of more than 4 kilometers were removed from the analysis to reduce the number of entries in the origin-destination matrix (for which the perceived shortest path was calculated). It is assumed that this roughly reflects the maximal acceptable distance for bicycle use in the case study area. The assumption is based on a recent travel survey of the case study area indicating that over 90% of cycling trips are of a distance below 5 kilometers (Eloy and Derré, 2014).

In this work, the demand side of the cycling network was modeled by reducing accessibility to a function of the availability of destinations in each zone and the cost of accessing those destinations (Iacono et al., 2010). The actual travel demand, however, is not considered in the analysis. There are different ways to estimate cycling demand. Usually, data from extensive travel surveys (e.g. Grisé and El-Geneidy (2018); Larsen and El-Geneidy (2011); Larsen et al. (2013); Lovelace et al. (2017) and Mahfouz et al. (2021)) or other sources such as bike-sharing system data (e.g. for the case study area Côme and Oukhellou (2014) and Nair et al. (2012)) is used to model travel flows between zones (Romanillos et al., 2016). The inclusion of such data could be an interesting topic for further analysis.

An important aspect to consider is the connection between neighborhoods across major street axes or obstacles such as rivers. It is important to avoid a situation where zones or neighborhoods become a series of islands isolated from each other (Mekuria et al., 2012; Parkin and Koorey, 2009). Bikeability assessments aim to analyse the connectivity of different parts of the cycling network and to identify areas in the city that are in some way disconnected from destinations. This is impressively shown in the work by Lowry et al. (2016) where a part of the city of Seattle, USA, is to a certain extent disconnected from the city center where most destinations are located. The paper shows that the installation of suitable cycling infrastructures on a highway crossing bridge would significantly improve bikeability of that disconnected area. Similar situations were not detected in this project and no areas stand out as being completely disconnected from important destinations. This indicates that the cycling network is quite mature and that most destinations can be reached by bicycle.

Bikeability was assumed to be worse moving away from the city center because there is a higher concentration of destinations in the city center. This was true especially for the central city area north of the river where a cluster with good bikeability was detected. However, the results have shown that bikeability values do not necessarily get worse toward the edges of the city. For example, a cluster with bad bikeability was identified south of the river in a very central area of the city. This indicates that the bicycle suitability analysis certainly influenced the bikeability analysis. A combination of comparably few destinations around an origin raster cell and a high concentration of street segments with lacking bicycle suitability lead to the lowest bikeability values. The same effect was observed in the area south of *Place Charles de Gaulle*, where many street segments with lacking bicycle suitability are located. The comparably low bikeability values in the northeast of the city can be explained by a lack of destinations in that area but also by the high concentration of street segments with slopes.

The proposed bikeability analysis can identify areas with potential for improvement of cycling infrastructures for different types of destinations. The results could be combined with other cycling infrastructure assessments to support decision-making.

Key messages:

- The routing algorithm (perceived shortest path) succeeds in detecting hills and streets with lacking cycling infrastructures and thus roughly models the route choice of cyclists.
- The proposed method allows identifying areas with potential for improvement of cycling infrastructures. Bikeability was assessed for the entire case study area using 250 x 250 meters raster cells and a distance threshold of 4 kilometers.
- The method allows calculating bikeability for different types of destinations.
  The destinations can easily be adapted according to the study goals.
- No areas that are disconnected from the cycling network were detected.
  The results could be combined with other cycling infrastructure assessments to support decision-making.

6.3 Overall Limitations

Of course, the chosen approach has several overall limitations, including those related to data sources and the model design.

R has been a suitable choice of software for this project. The programming language is becoming increasingly popular for geographical data and network analysis (R Core Team, 2020) and many of the packages used in this project are rapidly evolving (Lovelace et al., 2017). For some computational steps such as the preprocessing (merging of data) and network routing functions, other GIScience software might have provided more user-friendly options. The results and especially spatial patterns and possible locations for the improvement of cycling infrastructure were often difficult to illustrate since the aim was to show the results in the context of the entire city. However, using R allowed to develop fully reproducible methods that could also be applied to other case study areas.

A group of limitations relates to the data sources. While data collection processes are often well established in motorized transport, the lack of applicable data is a limiting factor for transport and urban planning studies that focus on cycling (Willberg et al., 2021). The increasing accessibility of Big Data collected from various sources such as sensors, bike-sharing systems, GPS devices, and social media (Romanillos et al., 2016), enables to uncover interesting mobility patterns and daily movements of people (Willberg et al., 2021). Such data could be helpful to further develop the method to achieve more reliable and representative outcomes that help to improve cycling infrastructures and to support the growth of cycling in cities (Nelson et al., 2020; Willberg et al., 2021). While data limitations strongly influenced the proposed methodology, the chosen data was generally well suited for the goals of this analysis. All data files are bound to include some errors (Mekuria et al., 2012) and the data used in this project was not corrected. Some issues with up-to-dateness were observed in this analysis - a limitation that needs to be considered when working with OSM data (Nelson et al., 2020). As stated in Abad (2019), encouraging volunteers to contribute to OSM can enhance this type of study immensely. To enhance the quality and detail of cycling data used in this project, a second data set by Apur was included. It was not assessed, however, whether the results would differ if OSM data would have been used.

Other limitations are related to the overall model design. Firstly, the cycling network was treated as a non-directed network. One-way streets were not be distinguished from two-way streets or by direction of travel. Mekuria et al. (2012) argue that most cycling trips are round trips and thus the trip needs to be doable by bicycle in both directions for people to choose this mode of transport. Even though there are many one-way streets in the case study area, they often can be used in both directions by cyclists. Furthermore, the routing did not aspire to be fully accurate but to give a realistic estimate of the (perceived shortest) distance between origin and destination. Since the cycling network of the case study area is quite mature, it was assumed that there generally are options to travel from all origins to all destinations in both directions. Nevertheless, using a directed network could be an interesting aspect to include in a similar analysis. Secondly, destinations and cycling infrastructures outside of the case study area were not considered, even though transport obviously does not stop at the city borders. This aspect is not considered in most studies of this field. It would therefore be interesting to include origins, destinations, and cycling infrastructures outside of the city in further assessments.

Finally, it is easy to forget the reality of planning processes when theoretically proposing possible cycling infrastructures that could be installed. Parkin and Koorey (2009) state that the planning and design of high-quality cycling infrastructures may take decades to complete successfully. The history of cycling in cities shows that the discourses and attitudes towards different modes of transport also play a crucial role and have in many cases been reflected in bicycle-friendly policies and cycling plans (Oldenziel and De la Bruhèze, 2011). The impact of government policies can not be neglected (Pucher and Buehler, 2008), which becomes evident when working with Paris as a case study area. For example, the speed at which bicycle-friendly measures were put into place during the COVID-19 is an impressive reminder that action can be taken quite rapidly if cycling is considered an important part of mobility in a city. Paris' efforts to become a cycling city have been ambitious in the past years and will presumably be further pursued. To support well-informed decisions in cycling planning, different methods such as the one proposed in this project can be used as tools to assess where to improve cycling infrastructures.

Chapter 7

Conclusion

This project set out to explore where cycling infrastructures in the city of Paris could be improved. The main data sources used in this project were OSM and Apur. A bicycle suitability analysis and a bikeability analysis were applied to identify potential locations for improvements of bicycle infrastructures. The proposed bicycle suitability analysis is based on two important factors that influence the route choice of cyclists: Traffic speed and the type of bicycle infrastructure provided. It distinguishes different levels of bicycle suitability and allows to precisely identify street segments with potential for improvement in terms of bicycle suitability. The proposed bikeability analysis shows for each origin zone the convenience and comfort of reaching destinations by bicycle. Bikeability is assessed for the entire case study area using 250 x 250 meters raster cells and a distance threshold of 4 kilometers. The method uses a gravity-based accessibility model that takes into account the perceived distance on the route between the origin and different types of destinations.

The main contribution of this project is a methodology that can support decision-making in bicycle planning by closing the identified research gaps. The proposed method can be applied with commonly available data, has clear outcomes, is reproducible, and can be applied to other case study areas. The identified street segments and areas with potential for improvement of cycling infrastructures need to be examined individually and should be further assessed in the context of the local policy goals. The proposed methodology could be used as a tool for network evaluation and development.

7.1 Future Work

Future work could expand the bicycle suitability assessment by adding more factors that influence the route choice of cyclists. For example, traffic volumes and intersections could be included in the analysis. Furthermore, it would be interesting to consider the design and maintenance of provided bicycle infrastructures. The bikeability assessment could be improved using smaller raster cells to model bikeability in more detail. Furthermore, bikeability could be calculated for different improvement scenarios to assess their effect on bikeability. Other interesting approaches would be to use a directional network, to include travel demand or trips and destinations outside of the case study area in the model. Finally, the inclusion of emerging data sources that uncover interesting mobility patterns of cyclists could help to further develop the method. These aspects could help to improve the tools that guide the planning and provision of bicycle infrastructures towards a more sustainable transport future.

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Appendix A

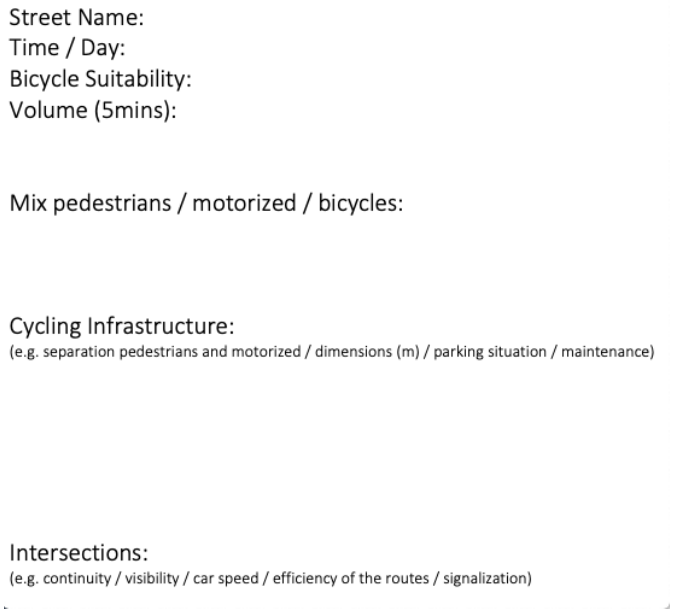
Data Overview

Data	**Source**
Cycling infrastructures in the Île-de-France region	Apur
Streets in the Île-de-France region	OSM
Points of interest & transport in the Île-de-France region	OSM
Zones 30 in the city of Paris	ODP
DEM of the Île-de-France region	IGN
Districts in the Île-de-France region	Apur
Parks in the Île-de-France region	Apur
Waterways in the Île-de-France region	Apur

TABLE A.1: Data used for this project and their sources. The Geofabrik download service was used to download OSM data. All data was downloaded between the 01/02/2021 and the 05/02/2021.

Appendix B

Empirical Evaluation Protocol



Street Name:
Time / Day:
Bicycle Suitability:
Volume (5mins):

Mix pedestrians / motorized / bicycles:

Cycling Infrastructure:
(e.g. separation pedestrians and motorized / dimensions (m) / parking situation / maintenance)

Intersections:
(e.g. continuity / visibility / car speed / efficiency of the routes / signalization)

Figure B.1: The protocol used for the empirical evaluation.

Appendix C

Lists of Potential Improvements

Street	Length	Street	Length
Boulevard Raspail	3.6	Boulevard Saint-Michel	1.0
Avenue de Flandre	2.6	Boulevard de l'Hôpital	0.9
Boulevard Malesherbes	2.5	Boulevard Haussmann	0.9
Rue de Vaugirard	2.4	Avenue Marceau	0.9
Rue Lecourbe	2.4	Avenue des Gobelins	0.9
Boulevard Exelmans	2.0	Boulevard Diderot	0.9
Avenue du Président Wilson	2.0	Boulevard Ornano	0.8
Avenue du Président Kennedy	1.9	Rue La Boétie	0.8
Avenue de New York	1.8	Avenue F. Delano Roosevelt	0.8
Avenue de Versailles	1.6	Boulevard Suchet	0.8
Rue de Rome	1.6	Rue de Châteaudun	0.8
Rue La Fayette	1.6	Boulevard Gouvion-Saint-Cyr	0.8
Rue Ordener	1.5	Avenue des Champs-Élysées	0.7
Cours de Vincennes	1.3	Avenue de France	0.7
Avenue de Villiers	1.3	Quai Saint-Bernard	0.7
Rue Réaumur	1.3	Boulevard Soult	0.7
Rue de la Convention	1.2	Avenue Foch	0.7
Avenue du Maine	1.2	Avenue de l'Opéra	0.7
Boulevard Henri IV	1.2	Boulevard de Bercy	0.7
Boulevard de Sébastopol	1.1	Rue du Faubourg Saint-Denis	0.7
Avenue du Général Leclerc	1.1	Quai François Mitterrand	0.7
Rue de Sèvres	1.1	Boulevard du Bois le Prêtre	0.7
Rue de Rennes	1.0	Rue du Départ	0.6
Rue de Tolbiac	1.0	Rue des Écoles	0.6
Boulevard des Batignolles	1.0	Avenue Mozart	0.6

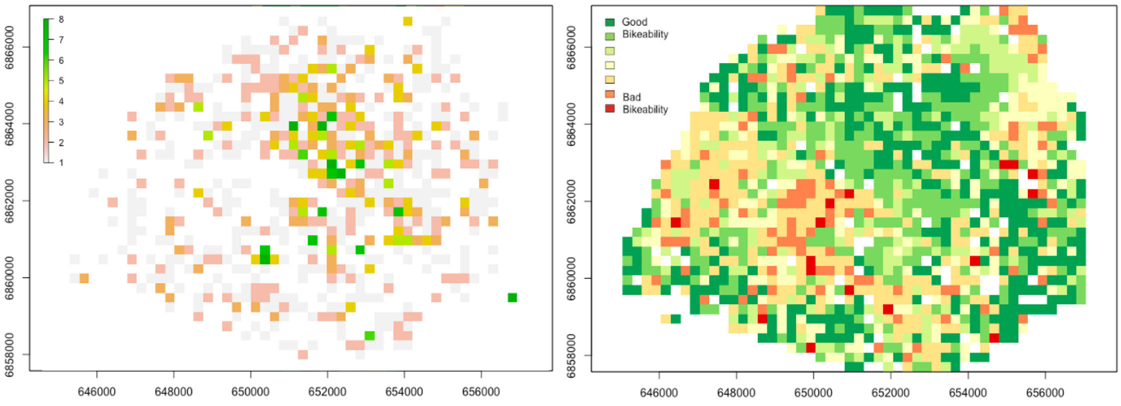
Table C.1: The 50 longest streets with bicycle suitability D. The lengths might deviate from reality because streets can consist of multiple line segments running parallel to each other.

Street	Length	Street	Length
Boulevard Pereire	3.8	Rue du Ranelagh	1.0
Avenue Foch	3.3	Boulevard Lannes	1.0
Avenue du Maine	2.5	Rue Saint-Honoré	1.0
Boulevard du Montparnasse	2.2	Rue Saint-Charles	1.0
Avenue de Breteuil	1.7	Place de la Porte Maillot	0.9
Avenue Victor Hugo	1.7	Boulevard Pershing	0.9
Boulevard Haussmann	1.6	Avenue Bosquet	0.9
Avenue de la République	1.5	Boulevard de Montmorency	0.9
Rue du Faubourg Saint-Honoré	1.5	Avenue des Ternes	0.9
Rue de Vaugirard	1.4	Avenue de Ségur	0.9
Rue de Javel	1.3	Rue Lauriston	0.9
Rue de la Croix Nivert	1.3	Boulevard d'Algérie	0.9
Boulevard Murat	1.3	Rue Caulaincourt	0.9
Boulevard Edgar Quinet	1.3	Avenue du Général Michel Bizot	0.9
Rue du Bac	1.2	Avenue George V	0.8
Boulevard de Port-Royal	1.2	Rue Vergniaud	0.8
Avenue Kléber	1.2	Rue de la Faisanderie	0.8
Boulevard Flandrin	1.1	Rue Didot	0.8
Avenue d'Iéna	1.1	Rue de la Convention	0.8
Avenue Paul Doumer	1.1	Avenue Duquesne	0.8
Rue des Plantes	1.1	Rue Galilée	0.8
Rue Saint-Dominique	1.1	Rue Jean de La Fontaine	0.8
Avenue Raymond Poincaré	1.1	Rue de l'Université	0.8
Rue d'Alésia	1.0	Rue Froidevaux	0.8
Rue de Grenelle	1.0	Rue Raymond Losserand	0.8

Table C.2: The 50 longest streets with bicycle suitability E. The lengths might deviate from reality because streets can consist of multiple line segments running parallel to each other.

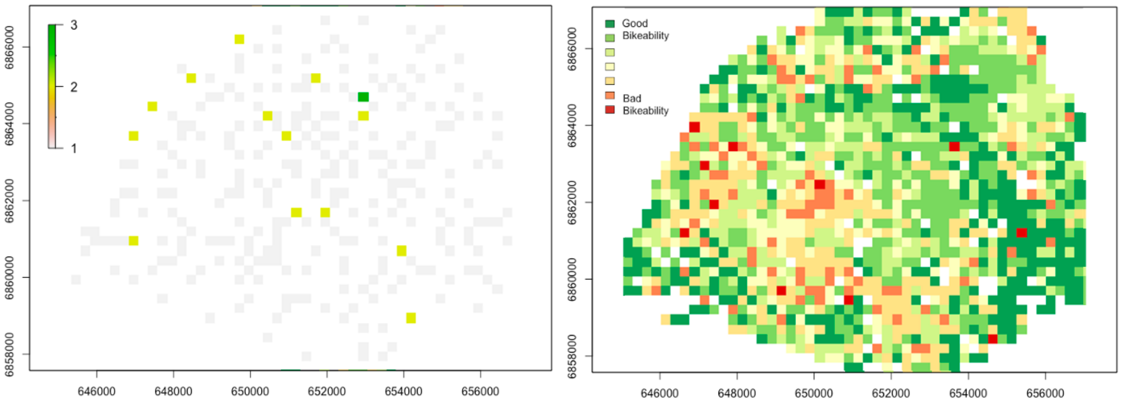
Appendix D

Destinations and Bikeability



(a) Destinations Leisure

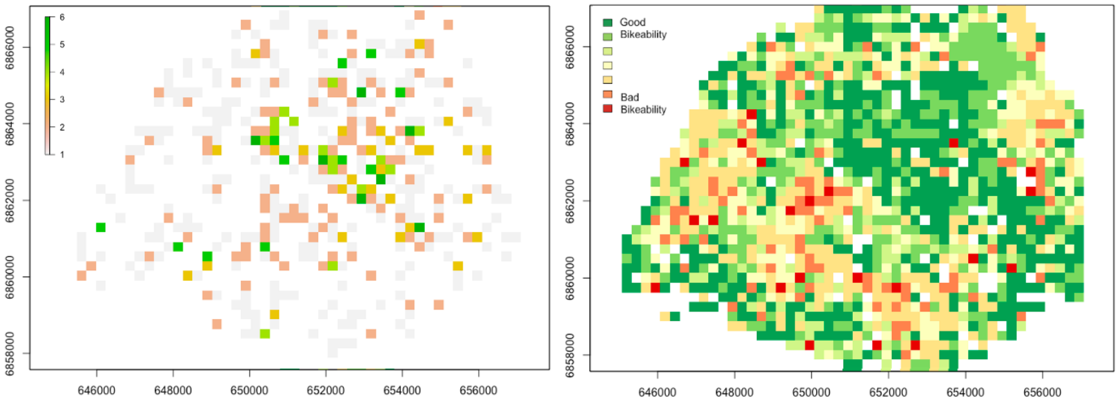
(b) Bikeability Leisure



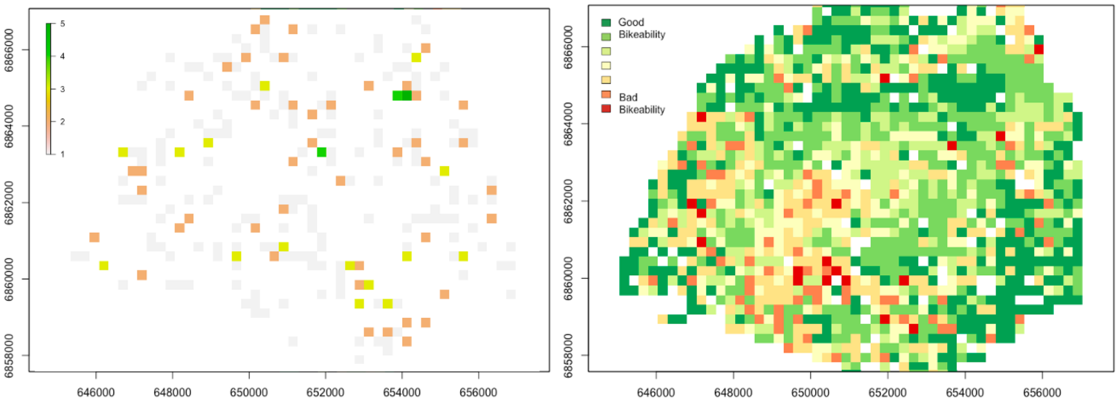
(c) Destinations Public Transport

(d) Bikeability Public Transport

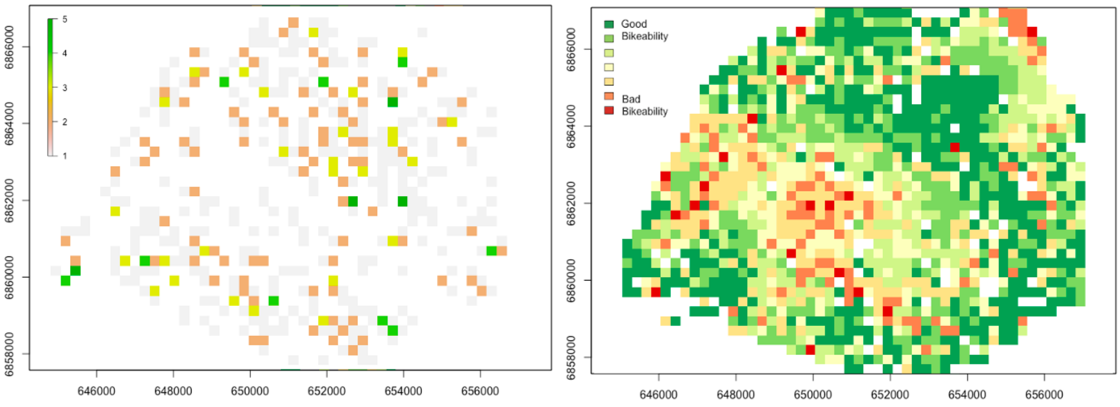
Figure D.1: The number of destinations and the bikeability of destination type Leisure (a + b) and Public Transport (c + d) in the city of Paris.



(a) Destinations Shopping (b) Bikeability Shopping



(c) Destinations Education (d) Bikeability Education



(e) Destinations City Functions (f) Bikeability City Functions

Figure D.2: The number of destinations and the bikeability of destination type Shopping (a + b), Education (c + d), and City Functions (e + f) in the city of Paris.

Personal Declaration

I hereby declare that the submitted thesis is the result of my own, independent work. All external sources are explicitly acknowledged in the thesis.

L. Wysling

Laura Wysling, August 2021