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Traffic coverage quality by bike in Switzerland: A comparison of cities' bikeability

GEO 511 Master's Thesis

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Abstract

Against the backdrop of sustainable spatial and transport planning, cities' authorities are implementing policies to promote cycling in urban areas. In Switzerland, with the recently put in place national law on cycle paths, a bike network should be constructed, providing access to important destinations. To increase cycling levels, cycling should be safe and desirable for a broad spectrum of the population. However, to date, a fully reproducible measure describing the favorability of a location in terms of the potential to cycle is lacking for urban areas in Switzerland. This thesis aims to develop a bikeability index to capture the traffic coverage quality by bike for the Swiss cities Bern, Lausanne, Winterthur and Zurich. Bike infrastructure data from OpenStreetMap (OSM) and Open Government Data (OGD) to model the spatial accessibility and the cycling quality on the routes to important destinations are the main data used in this project. The implemented gravity-based bikeability index allows to investigate how the traffic coverage quality by bike varies within and between the four chosen case study areas. It can therefore be used for site evaluations or to describe the micro location in terms of the potential to cycle. The proposed method further introduces a tool for policymakers, showing which areas are comparably most in need of improvements to the bicycle infrastructure. It indicates where potential improvements of bike infrastructures are most relevant to enhance bikeability in a municipality. This thesis focuses on the four Swiss cities Bern, Lausanne, Winterthur and Zurich. However, relying on publicly available data with nationwide coverage, the proposed method is fully reproducible for any urban area in Switzerland.

Keywords: Bikeability, bicycle infrastructure, sustainable cities, traffic coverage quality

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Abbreviations

BSS	Bicycle Sharing Systems
DEM	Digital Elevation Model
GPS	Global Positioning System
HCM	Highway Capacity Manual
LTS	Level of Traffic Stress
NGO	Non-Governmental Organization
OGD	Open Government Data
OSM	OpenStreetMap
SDG	Sustainable Development Goal
SSH	Secure Shell
UN	United Nations

1 Introduction

1.1 Research motivation

"Make cities and human settlements inclusive, safe, resilient and sustainable" (UN, 2015: 21)

Confronted with global challenges such as air pollution, traffic congestion, climate change, energy scarcity and physical inactivity (Frumkin et al., 2004), mobility has been identified as a pivotal sector for the realization of the United Nations' Sustainable Development Goals (SDGs). Particularly to realize SDG 11, which focuses on sustainable cities and communities, transport systems play a crucial role (UN, 2015). Transport accounts for around 20% of global carbon dioxide (CO_2) emissions. 74.5% of global CO_2 emissions in the transport sector stem from road vehicles (Ritchie, 2020). To make traffic more sustainable, transport and urban planning are focused on strategies to reduce automobile travel (Frumkin et al., 2004). Cycling has been widely recognized as an environmentally friendly and space-efficient mode of transport. Primarily in urban areas, where travel distances are short, cycling has a high potential to replace motorized private transport (Schmid-Querg et al., 2021). In addition to the environmental and spatial benefits, benefits of cycling to public health and the economy are well documented in previous studies (Brown et al., 2013; Osama et al., 2017). Because of its wide range of benefits for individuals and the community, governments and authorities around the world are implementing policies to promote cycling (Buehler and Dill, 2016). It has been shown that the regular use of bikes is positively associated with the cycling quality provided by the natural and built environment. Cycling policies should therefore include the provision of adequate bike infrastructure on people's routes between origins and destinations (Mekuria et al., 2012). Many authorities, predominantly in urban areas, want to improve the quality of the population's cycling experiences to increase levels of cycling (Krizek et al., 2009).

In Switzerland, the country on which this thesis focuses, current cycling numbers are rather low. This is particularly true in comparison to the role model countries for bike traffic, the Netherlands and Denmark. Of the 30 kilometers (km) that a Swiss person travels on average per day, 21.1 km are covered by private motorized transport, 5.9 km by public transport, 1.6 km by foot, 0.9 km by bicycle and 0.4 km by other modes of transport (BFS and ARE, 2023). Swiss transport policy has been striving for several years to increase the share of bike traffic, increasing the relevance of cycling in transport and spatial planning (ASTRA, 2023a). An important step for the promotion of bike traffic in Switzerland is the national law on cycle paths (Pro Velo Schweiz, 2023). It has been in place since the beginning of the year 2023 and has the main goal to build a better and safer bike network. Improvements of bike infrastructures should foster a bike culture, ultimately increasing cycling numbers.

Given the observed positive association between the cycling quality provided by the built and physical environment and the regular use of bikes, it should be evaluated how favorable it is to use a bike from a certain location. Similar measures capturing traffic coverage quality have already been well established for motorized private transport or public transport in Switzerland (ARE, 2022). However, a measure capturing the traffic coverage quality by bike is missing so far. Assessing and comparing the traffic coverage quality by bike of the places where people live is a necessary first step to see where it is already convenient to use a bike and where further improvements of bike infrastructures are needed. Since the potential to cycle from a location of residence positively influences bike use, the traffic coverage quality by bike can further be seen as an indirect dimension of the sustainability of buildings.

Section 1.2 defines the main goals and the research questions of this thesis. Chapter 2 reviews the literature on the role of cycling in spatial and transport planning, on the factors influencing if and how people use bikes, and on the assessment of how suitable streets and areas are for cycling. Additionally, bikeability, the key concept of this thesis, is introduced. Chapter 3 examines the case study areas by illustrating the role of cycling in Switzerland and its cities. It further describes the data used in this project. The methodology applied to address the research questions is presented in Chapter 4. In Chapter 5, the results of the analysis are presented before the results are discussed in Chapter 6. The discussion focuses on answering the research questions in the context of previous literature, but also on reflecting the used data and the limitations of the chosen approach. Additionally, it highlights possible directions for further research. Finally, conclusions of the project are drawn in Chapter 7.

1.2 Objectives and research questions

The main objective of the thesis is to develop a model describing how suitable for cycling urban areas in Switzerland are. The model output should allow to identify how convenient it is to use a bike from locations of residence, and therefore how prone people are to use a bike for home-based utilitarian trips. Some of the most populated cities in Switzerland, namely Zurich, Winterthur, Bern and Lausanne, are chosen as the case study areas. However, based on the used method and commonly available data, the developed model should be fully reproducible and applicable to any urban area in Switzerland.

Based on the research gaps highlighted in Section 2.5, the following research questions have been formulated for this thesis:

- **RQ1**: How does the level of bikeability compare within and between different Swiss cities?
- **RQ2**: Which areas are comparably most in need of improvements to the bicycle infrastructure?

2 Literature review

In this chapter, existing research on bike traffic, its determining factors and measures to assess the quality to cycle is presented. First, the past and today's role of cycling in spatial and transport planning is summarized in Section 2.1. Section 2.2 explores how bike infrastructure affects peoples' decision to cycle. Literature dedicated to the question of where cyclists ride is reviewed in Section 2.3. In Section 2.4, the central concept of this thesis, bikeability, is defined. The section further illustrates how the concept of bikeability can be used to capture the traffic coverage quality by bike. Finally, Section 2.5 presents the identified research gaps addressed in this project.

2.1 Role of cycling in spatial and transport planning

In transport planning, spatial planning and academics, cycling was largely neglected until recent decades (Pucher and Buehler, 2017). Having been omnipresent on the streets in many European cities between the First World War and the late 1950s, the use of bikes reached an all-time low thereafter (Oosterhuis, 2016). A surge of car ownership combined with urban sprawl led to a sharp fall in cycling (Pucher and Buehler, 2008). The trend was further reinforced by a decline in the social status of the bike among the population and car-centered policies. Motorized traffic was considered a part of economic and technological progress. The bike was increasingly seen as an outdated and inefficient way of transportation by traffic engineers, urban planners and policymakers (Oldenziel and de la Bruhèze, 2011; Oosterhuis, 2016). Cities' priority was to satisfy and facilitate increased car use. Roadway capacity and parking supply for cars were expanded. The interests of pedestrians and cyclists were marginalized (Hass-Klau, 1990).

A shift in urban and transport policies in the 1970s led to another increase in bike use (Pucher and Buehler, 2008). The advantages of cycling have first been highlighted by cycling activists, followed by policymakers, politicians, urban planners, social scientists and public health experts (Oosterhuis, 2016). Especially in Germany, Denmark and the Netherlands, the first and most determined policies have been implemented to promote more and safer cycling (Pucher and Buehler, 2008). The successful cycling infrastructure construction programs and policies implemented by cities in those countries were later adopted by many other cities in Europe, North America and Australia between the 1980s and 2000s (Pucher et al., 2011; Pucher and

Buehler, 2016). Consequently, there has been significant growth in cycling numbers in those cities (Pucher and Buehler, 2017), even though per-capita income, suburban development and car ownership have been growing (Pucher and Buehler, 2008). The result in urban and transport planning in the 21st century has been a paradigm shift, away from motorized transport to a more sustainable form of mobility (Fishman et al., 2013). In the context of urban planning processes focusing on more sustainable modes of transport, the bike has an important role since the 2010s. The promotion of cycling is seen as an effective way to realize 11 out of the 17 SDGs in the UN's 2030 agenda, as it contributes to environmental, social and economic sustainability (Castañon and Ribeiro, 2021; UN, 2015).

Today, urban and transportation planning and public health aim to make cities more sustainable and livable by reducing automobile travel and promoting active transportation (Frumkin et al., 2004). The two active modes of transport walking and cycling are the most sustainable modes of transport (Chakhtoura and Pojani, 2016). Bikes have the highest potential to replace motorized transport on trips with a relatively short travel distance (Winters et al., 2013). As a mode of transport with no air pollution, the widespread use of bicycles has the potential to significantly contribute to the decarbonization of the mobility sector (Buehler and Pucher, 2021; Pucher and Buehler, 2017). Moreover, cycling causes no noise emissions and improves the physical and mental health of travelers (Brown et al., 2013; Schmid-Querg et al., 2021). Bicycle infrastructure requires less space and causes lower costs compared to other modes of transport (Pucher and Buehler, 2008). On the level of individuals, the relatively low user costs make the bike one of the most equitable transport modes (Hamidi et al., 2019; Pucher and Buehler, 2008). Transport literature highlights the importance of potential access to opportunities for political, social and economic participation among the population (Lucas, 2012). A concept gaining momentum in debates around spatial accessibility is the 15-Minute City (Ferrer-Ortiz et al., 2022): In a polycentric city, residents should have access to all important facilities by bike or foot in less than 15 minutes (Duany and Steuteville, 2021). With short travel distances, a reliance on active modes of transport and equal access to various destinations, the 15-Minute City seeks to make cities more livable for citizens (Moreno et al., 2021). Among the destinations that should be reachable are grocery stores, for example, but there is further growing interest in accessibility to public facilities, such as train stations or schools (Li et al., 2021).

Given the highlighted importance of cycling, especially for urban areas, many cities are implementing policies and programs to raise cycling levels (Buehler and Pucher, 2021; Codina et al., 2022). For effective interventions, it is crucial to know which factors positively influence the decision to choose the bike as the mode of transport. Common bike promotion initiatives seek to increase the cycling experience of the built environment, predominantly through bike infrastructure construction.

2.2 Bicycle infrastructure and mode choice

Previous research has identified a variety of factors determining whether people use the bike as a main mode of transport or not. Features affecting cycling rates include socio-demographic characteristics of the population (Codina et al., 2022), culture (Haustein et al., 2019), topography (Rietveld and Daniel, 2004; Winters et al., 2010a), climate (Hyland et al., 2018; Parkin et al., 2007) and distance to trip destinations (Nielsen and Skov-Petersen, 2018). However, government policies are at least as important as the aforementioned factors: Land-use policies, urban development policies, transport policies and housing policies (Codina et al., 2022; Pucher and Buehler, 2008).

For cycling, bicycle infrastructure policies are essential (Dill, 2009; Muhs and Clifton, 2016). Compared to walking, the infrastructure is more important for cycling (Kellstedt et al., 2021). Previous studies have shown that there is a positive relationship between the regular use of bikes and the cycling quality of bike networks (Buehler and Dill, 2016; Buehler and Pucher, 2021). Altering the characteristics of the built environment is therefore seen as an effective way to promote active travel by bike (Vale et al., 2016). Aggregated cross-sectional data and longitudinal studies show that the construction of adequate bike infrastructure leads to an increase in cycling levels (Dill and Carr, 2003; Monsere et al., 2014). It has further been estimated that the benefits of increased cycling are four to five times higher than the costs of new cycling infrastructure investments, for example, because of positive health effects (Cavill et al., 2008).

To increase the cycling modal share, the presence of suitable cycling infrastructure plays a crucial role (Hull and O'Holleran, 2014; Pucher et al., 2010). Bike infrastructure should not just enable cycling, but encourage it by making its regular use safe and convenient (Handy and Xing, 2011). According to the Netherlands' bicycle infrastructure manual, successful bike networks fulfill five requirements: Safety, cohesion, directness, comfort and attractiveness

(CROW, 2016). These requirements, shown in Figure 1, are consistent with cyclists' preferences (Gerike et al., 2022). Perceived safety is the fundamental requirement for bike uptake (Hull and O'Holleran, 2014). Lacking perceived safety is a major deterrent to cycling (Aldred, 2016; Parkin et al., 2007). Along with the avoidance of conflicts with pedestrians or public transport, it is the perceived safety from motorized traffic that is particularly important (Codina et al., 2022; Kamel et al., 2020). Bicycle infrastructure on one very short section does not change much concerning the perceived safety and convenience of a large area. It should rather be coherent, forming a bike network, which in turn is integrated into the transport network (Dill, 2009). Transport literature has increasingly been discussing the potential of intermodality, the combination of at least two transport modes for one trip. Bike networks well connected to public transport networks, for example, increase the attractiveness of the two transport modes mutually (Hegger, 2007).

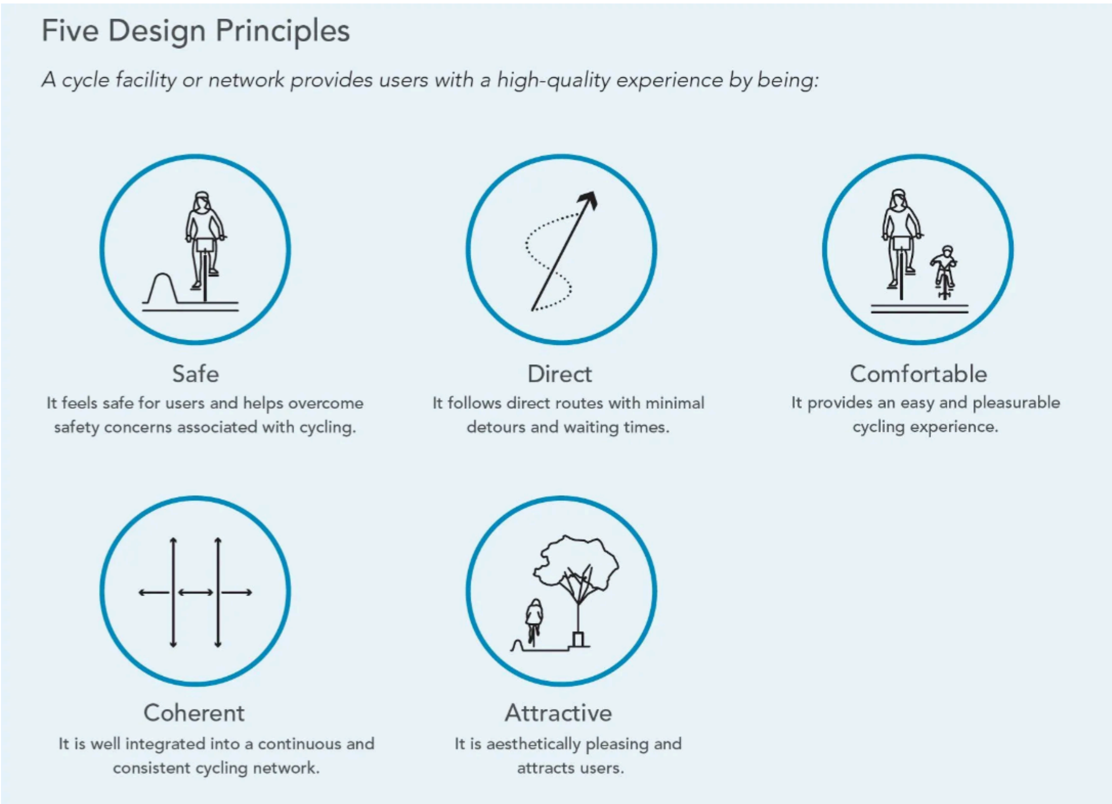


Figure 1 Five design principles for bike networks according to CROW (2016). Illustration by Greater Auckland (2017).

However, the selection of the optimal type of bicycle infrastructure on a given street is not straightforward. The motto "build it, and they will come" (Cervero et al., 2013) is not a panacea (Arellana et al., 2020). The construction of bike infrastructure requires careful and adequate planning (Arellana et al., 2020). Not only bike infrastructure availability, but also its quality (i.e., its width) influences the cycling experience (Mueller et al., 2018). In cities, scarce street space is a major challenge to plan and implement bike infrastructure (Di Mascio et al., 2018). Moreover, (potential) cyclists have different levels of sensitivity to perceived comfort and safety of bike infrastructures. Dill and McNeil (2013) developed a method to classify a population into four types of cyclists, defined by Geller (2006): "No Way No How", "Interested but Concerned", "Enthused and Confident" and "Strong and Fearless". People belonging to the "No Way No How" group do not want to or are not able to cycle, independent of the infrastructure present. The "Interested but Concerned" group includes people who would like to cycle more often if the infrastructure would be better to ensure safety. The "Enthused and Confident" cycle regularly, but expect certain infrastructures. Cyclists from the "Strong and Fearless" group feel comfortable and safe on streets without any dedicated bike infrastructure. This typology of the population was the basis for the Level of Traffic Stress (LTS), a framework that classifies streets depending on the effect their infrastructures have on cyclists' stress (Mekuria et al., 2012). Four levels of traffic stress roughly correspond to the four types of cyclists introduced by Geller (2006). Streets with a LTS 3, for example, have a LTS that is maximally accepted by the "Enthused and Confident". Streets with such a LTS are not suitable for the "Interested but Concerned" (Cabral and Kim, 2020). The distinction between the different levels of traffic stress allows to assess the required type of bicycle infrastructure, such that (potential) cyclists choose to use a bike (Mekuria et al., 2012). Policies with the goal of increasing cycling numbers are often targeted at citizens belonging to the "Interested but Concerned" group (Buehler and Pucher, 2021; Dill and McNeil, 2013).

Using Dutch, German and Danish cities as case study areas, Pucher and Buehler (2008) show that separate cycling facilities along roads with much traffic and at intersections together with traffic calming measures in residential neighborhoods increase cycling rates. Winters et al. (2010a) underline the significance of traffic calming measures for increasing cycling rates. Similarly, Pucher et al. (2010) state that cyclists want bike lanes instead of riding in mixed traffic. According to McNeil (2011), this is particularly true for infrastructure types physically separating cyclists from other road users. Along with bicycle infrastructure on roads, studies have also considered the role of parking spaces (Lin and Wei, 2018). It is, however, not clear whether an increase in parking spaces encourages more cycling, or if a lack of such facilities dissuades from bike use (Lin and Wei, 2018; Pucher et al., 2010).

To increase the willingness to cycle, the implementation of bike infrastructure should go together with a change in attitudes of the population and other forms of public policy: Land use planning and bicycle education (Haustein et al., 2019). Policy packages produce the best results (Iwińska et al., 2018). Rietveld and Daniel (2004) distinguish between push and pull policies to make cycling more attractive. They underline that along with policies focusing on cycling, other modes of transport should also be made less comfortable and more costly. An example of push policies are fewer parking areas and lower speed limits for motor vehicles.

Nevertheless, separate cycling facilities are the cornerstone to increase cycling numbers. They make the different types of cyclists feel convenient, comfortable and safe (Pucher and Buehler, 2008). Especially along streets with high volumes or high speeds of motorized traffic, they are the key. The higher the degree of separation, the stronger the preference and perceived safety (von Stülpnagel and Rintelen, 2024). The hierarchy of preference for different types of bike infrastructures looks as follows: Separate paths, cycle lanes and roadways with mixed traffic (Buehler and Dill, 2016). Separate bike facilities do not automatically imply, but they are necessary to ensure that cycling is made desirable and feasible for a broad spectrum of the population (Garrard et al., 2008). Buehler and Dill (2016) differentiate between three different kinds of bike facilities:

- Bike lanes: With bike lanes, cyclists are not physically separated from motorized traffic. They are separated by lines painted on roadways instead. There is a considerable variation in quality and width within and between cities and countries. However, the infrastructure type adds a perception of safety compared to cycling in mixed traffic (Akar and Clifton, 2009).
- Cycle tracks: They can be either placed on or adjacent to roadways and physically separate cyclists from motorized traffic. The separation is typically implemented by barriers, curbs, or space buffers with bollards (Furth, 2012). Cycle tracks are associated with increased cycling levels after installation (Goodno et al., 2013).
- Bike paths: As cycle tracks, bike paths physically separate cyclists from motorized traffic. However, in contrast, they are physically separated from and in distance to roadways, typically running along waterfronts or through parks. They are associated with an increase in number of bike trips after installation (Krizek et al., 2009).

2.3 Which route do cyclists choose?

Bike infrastructure is not just a determinant for bike mode choice, but also among the important factors influencing the decision where cyclists ride. More generally, cyclists consider characteristics of the physical and built environment for their route choice. It has been shown that cyclists mostly do not choose the shortest route (concerning time or distance) between origins and destinations, but consider comfort and safety when choosing their routes (Larsen and El-Geneidy, 2011; Sener et al., 2009; Winters et al., 2010b). Until recently, the analysis of cycling route choice was mostly based on stated preference surveys (Buehler and Dill, 2016; Sener et al., 2009). In surveys such as the one conducted by Winters et al. (2010b), individuals are asked to evaluate routes based on their characteristics or which type of facility they prefer. Stated preference studies have the advantage that they can be implemented with low costs and that they allow to consider alternatives, e.g., facilities not yet present (Zimmermann et al., 2017). However, their main limitation is that they capture claimed behavior. Numerous works have described differences between observed and claimed behavior (Sener et al., 2009). To capture the trade-offs cyclists actually make when choosing their routes, recent analyses on route choice are based on revealed preference data. They are mostly based on collected GPS data of cyclists, which are matched to the cycling network (Broach et al., 2012; Reggiani et al., 2022; Zimmermann et al., 2017). The comparison of the actual traveled route to the shortest possible route reveals how much a cyclist is willing to detour from the shortest possible route to ride on a given infrastructure type. The studies mostly reveal the route preference of the average cyclist (Krizek et al., 2007; Menghini et al., 2010). The average behavior is useful to understand which factors deter and attract cyclists in general. The averaging, however, discards the individuals' route preferences (Reggiani et al., 2022). As already noted in the previous section, preferences are not homogeneous among cyclists. For example, the route choice may be different for utilitarian trips than for recreational trips (Beenackers et al., 2012).

Average detour rates found in previous studies range between 8% and 93% (Reggiani et al., 2022). According to Broach et al. (2012), average detours from the shortest possible route amount to 11% in Portland, USA. Longer average detours are found by similar studies with 40% in Texas, USA (Sener et al., 2009) and 67% in Minneapolis, USA (Krizek et al., 2007). Factors highlighted to be relevant for the route choice in previous literature are travel time/length, type of intersection, gradient, presence of bike infrastructure, traffic volume and cycling experience and age of cyclists (Menghini et al., 2010).

The slope affects cyclists' comfort and perceived safety. Broach et al. (2012) find that cyclists are willing to take a detour three times longer compared to the shortest distance to not encounter slopes higher than 6%. Additionally, cycling uphill makes it harder for cyclists to keep balance and cycling downhill is a potential danger because of high cycling speeds (Baker and Schmidt, 2017; Pestalozzi and Stäheli, 2012).

On the level of street segments, it is rather the perceived risk of conflict that is important for the route choice of cyclists and not the objective safety, i.e., the frequency of accidents (Hull and O'Holleran, 2014). If no separate bike infrastructure is present, the behavior of cyclists is highly dependent on the characteristics of motorized transport. Because of the perceived safety, cyclists prefer roadways with low volumes of motorized traffic, fewer travel lanes, no car parking and slower speeds (Buehler and Dill, 2016; Winters et al., 2010a). For bike facilities cyclists are willing to take a detour to use them. Separate facilities are preferred by cyclists (Broach et al., 2012; Zimmermann et al., 2017). Physically separated facilities such as bike paths or cycle tracks are preferred over cycle lanes (Buehler and Dill, 2016). For example, Tilahun et al. (2007) find that cyclists want to detour 20 minutes to ride on bike paths instead on roadways. A study of work commuters in the UK shows that cyclists are willing to take longer travel times for cycle paths instead of lanes (Wardman et al., 2007). Moreover, riding on bike paths is perceived as safer and more convenient than on multi-use paths, e.g., shared with pedestrians (Vedel et al., 2017).

Cycling behavior is influenced not only by street attributes, but also by intersections and their characteristics. For cyclists, intersections are perceived as sources of delay and conflict (Heinen et al., 2010). Studies investigating specific intersection characteristics have shown that cyclists do not want to encounter traffic signals or stop signs at intersections (Caulfield et al., 2012; Menghini et al., 2010). Dill and McNeil (2013) mention in their study that 68% of all bicycle crashes occur at intersections. With dedicated infrastructure and if cyclists are prioritized, intersections are perceived as safer (CROW, 2016). A comparison conducted in five US cities shows that cyclists feel the safest at intersections with separate bicycle signal phases. Bicycle traffic signals reduce conflicts with turning motor vehicles (Monsere et al., 2014). The perceived safety at intersections further increases with bike boxes (Dill et al., 2012). Bike boxes are installed in front of the stop sign for motorized vehicles, increasing the visibility of cyclists (Buehler and Dill, 2016).

A property influencing route choice through aesthetic qualities and comfort, rather than perceived safety, are green and aquatic surroundings (Grigore et al., 2019). Natural elements are generally perceived as attractive, lowering stress, and having a positive effect on an individual's mood (Ulrich et al., 1991). In warm temperatures and strong insolation, green areas and water bodies further have a cooling effect, e.g., trees providing shadow (Aram et al., 2019; Erath et al., 2017). Wahlgren and Schantz (2012) state that the presence of green areas is not the main factor influencing the decision to cycle. However, in their study conducted in Stockholm, Sweden they conclude that once people are cycling, they prefer green surroundings. Similarly, Krenn et al. (2015) find that green and aquatic areas are positively related to the traveled route among cyclists in Graz, Austria.

2.4 Bikeability: Traffic coverage quality by bike

In the two previous sections, it has been shown how the degree of suitability for biking has a strong influence on peoples' decision if they cycle and where. Due to cycling's significance in spatial and transport planning for the realization of the SDGs (described in Section 2.1), there is a growing interest in science and among policymakers for measures to capture how suitable for biking a certain location or area is (Krenn et al., 2015; Wysling and Purves, 2022). Such measures show where people have a strong propensity to cycle and where further improvements of the built environment are needed.

A variety of measures have been developed to characterize the locational quality of single properties or whole neighborhoods (Schirmer et al., 2014). One of the most central attributes of a location is accessibility (Geurs and van Wee, 2004). Hansen (1959: 73) defines accessibility as "the potential of opportunities for interaction." In this thesis, the more comprehensive conceptualization provided by Geurs and van Wee (2004: 128) is adopted. They define it as "the extent to which land use and transport systems enable (groups of) individuals to reach activities or destinations by means of a (combination of) transport mode(s)."

In the context of the SDGs, the subgroup of metrics focusing on the accessibility of built environments by different modes of transport become increasingly important. These metrics are also called traffic coverage qualities. They capture the spatial accessibility from a location with a certain transportation mode and therefore describe a potential (Hamidi et al., 2019). To what degree people actually use the potential accessibility, i.e., depending on individual-level characteristics, is not considered (Penchansky and Thomas, 1981). In the fields of transport and spatial planning, these measures are used to identify locations with a need for further improvement concerning coverage quality or areas with a high development potential due to their high spatial accessibility. In Switzerland, the case study area of this thesis, the most popular metric defining traffic coverage quality in planning are the public transport quality classes. Considering the distance to public transport stations and their service level, the metric indicates the degree of potential access by public transport from any location in Switzerland (ARE, 2022). A similar metric has also been developed to describe the degree of spatial accessibility by car.

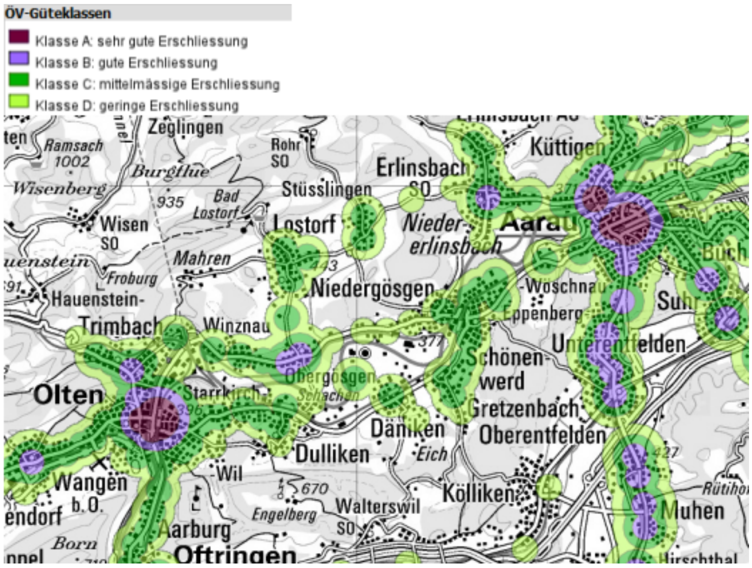


Figure 2 Public transport quality classes. Illustration by ARE (2022).

However, a corresponding metric for the accessibility or traffic coverage quality by bike in Switzerland is missing so far. Transport studies in general, have had a focus on the accessibility of motorized private transport (Heinen et al., 2010). There is relatively limited literature on the accessibility by active modes of travel: Walking and cycling (Codina et al., 2022; van Wee, 2016). The main reasons for the relatively scarce literature are the lack of reliable data and computational power (Iacono et al., 2010). Nevertheless, scientific literature provides measures to capture the suitability for biking of single locations or areas. The most popular approach in the literature to assess the built environment concerning cycling is bikeability (Arellana et al., 2020). There is no consensus on the definition of the term bikeability (Kellstedt et al., 2021;

Muhs and Clifton, 2016). In this thesis, the definition provided by Lowry et al. (2012: 41) is adopted. They distinguish between three concepts to assess how well a location or area supports cycling:

- Bicycle suitability: "Assessment of the perceived comfort and safety of a linear section of bikeway (the term bikeway includes shared-use paths and any roadway where bicycle travel is permitted)"
- Bikeability: "Assessment of an entire bikeway network in terms of the ability and perceived comfort and convenience to access important destinations"
- Bicycle friendliness: "Assessment of a community for various aspects of bicycle travel, including bikeability, laws and policies to promote safety, education efforts to encourage bicycling, and the general acceptance of bicycling throughout the community"

2.4.1 Bicycle suitability

As the definition by Lowry et al. (2012) shows, with bicycle suitability the levels of analysis are the streets and paths in a network. Numerous methods have been developed to assess bicycle suitability, but all aim to provide a rating or score for segments of a network depending on their perceived comfort and safety for cyclists (Lowry et al., 2012). They combine the number of points or score for each individual attribute under consideration into a final bicycle suitability score (Lowry et al., 2012). The characteristics considered are typically factors that have been identified to influence cyclists' route choice (compare Section 2.3). The methods differ, however, in the attributes they consider, the scoring system and how the sub-scores are combined into the final bicycle suitability score (Kazemzadeh et al., 2020; Lowry et al., 2012).

After extensive research over the last three decades, the bicycle suitability measure most common is bicycle level of service (BLOS). It evaluates the level of service of streets and intersections for cyclists (Arellana et al., 2020; Kazemzadeh et al., 2020; Landis et al., 1997). A state-of-the-art BLOS method has been developed by the Transportation Research Board (TRB, 2000) in the US for the Highway Capacity Manual (Lowry et al., 2012). It is based on previous studies, and it aims to improve the Highway Capacity Manual (HCM) for bicycle travel (Lowry et al., 2012). The HCM describes methods to assess the level of service for different transportation modes. It has been widely applied in transportation planning and safety analysis. Originally, it has been developed for the US, but many countries have modified and adopted the HCM (Yang, 2022). Among the ten characteristics used to calculate BLOS for streets are the width of bike lanes, vehicle traffic speed and vehicle traffic volume. As in Figure 3, the attributes are weighted and combined into an overall BLOS score on a range from A to F. A BLOS score of A describes streets with the highest level of service and a BLOS of F links with the lowest perceived comfort and safety.

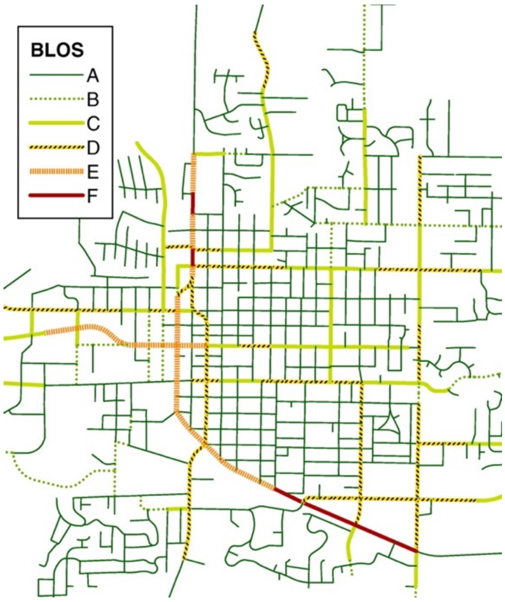


Figure 3 BLOS (A-F) for street segments in a network. Illustration by Callister and Lowry (2013).

However, factors not related to street infrastructure or traffic are not reflected by BLOS (Grigore et al., 2019), even though cyclists' route choice is also influenced by other factors, such as the topography or the presence of green and aquatic areas (compare Section 2.3). As the definition provided by Lowry et al. (2012) shows, bicycle suitability describes perceived comfort and safety in general, and is not restricted to bike infrastructure. More recent studies therefore additionally include factors relevant to route choice not related to bicycle infrastructure to model bicycle suitability (Grigore et al., 2019; Wysling and Purves, 2022).

The degree of bicycle suitability of a single street segment does not allow to draw conclusions on the bikeability of a given location or area, as it does not consider the network and spatial accessibility to important destinations. The construction of a cycle track along a single street segment is not sufficient to increase bikeability. The cycle track must be part of a wider bike network (Codina et al., 2022; Muhs and Clifton, 2016) and particularly at locations providing safe and comfortable routes for people to reach important destinations (Grigore et al., 2019). Nevertheless, bicycle suitability assessments can be a central element in bikeability analyses to describe the traffic coverage quality by bike.

2.4.2 Bikeability indices

Bikeability builds on the concept of bicycle suitability and additionally considers the network and the spatial separation between origins and destinations. Whereas bikeability literature is rather recent, walkability research has a longer history (Codina et al., 2022; Grigore et al., 2019). Walkability describes the quality of the built environment in supporting the movement of pedestrians (Erath et al., 2017). Both concepts are multidimensional, as they consider different aspects of the built environment (Kamel et al., 2020; Winters et al., 2013). Among the methods to capture bikeability, bikeability indices are particularly popular (Codina et al., 2022). Schmid-Querg et al. (2021: 2) even define bikeability as an "indexation of the environment in which cycling is taking place and how an area supports choosing the bicycle as a mode of transport." They describe the potential for cycling from a given location (propensity among the population). A bikeability index of a city is a useful tool for policymakers and the general public (Kamel et al., 2020). It allows to identify areas in need to improve cycling conditions, to monitor changes over time, and to communicate with a city's population (Codina et al., 2022). Furthermore, bikeability indices can be used to investigate the variation between different cities and not just within a single city (Codina et al., 2022). Most developed bikeability indices include spatial accessibility to jobs, while other types of destinations are less considered (Hamidi et al., 2019). Nonetheless, other types of destinations are also important to capture the general bikeability, as they affect travel behavior (Iacono et al., 2010).

One subgroup of bikeability indices is of an additive type. They first give scores to different considered characteristics in the surroundings of a location to then integrate them into a final bikeability score on a regular spatial grid (Krenn et al., 2015; Schmid-Querg et al., 2021; Winters et al., 2013). The scores of the different characteristics are added to one number for each grid cell. This number is the index value and describes the bikeability of a given cell (Schmid-Querg et al., 2021). The addition of values for the different characteristics of each grid cell is a weighted overlay analysis, a method related to the concept of map algebra (Tomlin, 1994). Krenn et al. (2015) first compare the actual taken route to the shortest possible route of a sample of bicycle trips in Graz, Austria to determine factors influencing route choice. The environmental characteristics found significant are: Cycling infrastructure, main roads without parallel bicycle lanes, presence of separated bicycle pathways, topography and green and aquatic areas. For every cell of a regular hectare grid, each identified component is scored separately between 1 and 10 depending on its quality to support cycling. The final bikeability index is computed as the sum of the components' scores. Similarly, Codina et al. (2022) calculate a bikeability index on a regular grid for Barcelona, Spain. But their final bikeability index is the weighted sum of the different indicators (traffic, infrastructure, connectivity, parking spaces and topography). The weights of each component are assigned based on a travel survey and previous literature.

However, the described additive bikeability indices do not include the accessibility to destinations (Schmid-Querg et al., 2021). Only a few methods consider the route to destinations. It might be that a street has a high bicycle suitability, but it does not lie on the route to important destinations (Lowry et al., 2012). Location-based accessibility measures instead, consider both transport components and land use (Geurs and van Wee, 2004). The most common operationalizations of these measures are distance-based or gravity-based (Miller, 2018). Distance-based accessibility measures are usually implemented by one of the following approaches (Apparicio et al., 2008): Distance to closest destination, number of destinations within a given distance or travel time, mean distance to all destinations and the mean distance to the n closest destinations.

In planning practice, gravity-based approaches are one of the most used measures of spatial accessibility (Geurs and Östh, 2016). They have a good balance between the ease of interpretation of results and complexity (Hamidi et al., 2019). Gravity-based approaches are based on Hansen's model of accessibility (Hansen, 1959), which discounts destinations using the cost to reach them (Geurs and van Wee, 2004). The weight of a destination is given by an impedance function (Vale et al., 2016). The impedance function (distance decay function) defines how the weight of a destination evolves depending on its cost to be reached. The cost can be travel times, travel distance or generalized costs. Usually, the impedance function is monotonically decreasing (Reggiani et al., 2011). Thus, destinations farther away are less valued compared to nearer destinations. Impedance functions frequently used are inverse power, modified Gaussian, or negative exponential functions (Vale et al., 2016). Some implemented measures do not further differentiate the opportunities by their attractiveness (Apparicio et al., 2008; McNeil, 2011). However, the approach allows to consider the attractiveness of opportunities, e.g., represented by the shopping square footage or the number of jobs (Lowry et al., 2012).

The first study computing a gravity-based bikeability index considering cycling quality was conducted by Lowry et al. (2012). The integration of cycling quality into the accessibility calculation allows to consider both cycling quality and spatial accessibility between origins and destinations (Schmid-Querg et al., 2021). This makes bikeability indices a useful tool to describe the traffic coverage quality by bike. They calculate a bikeability index for Moscow, Idaho, USA using scaled network distances as costs. Each street segment is scaled by a factor depending on its modeled bicycle suitability, representing perceived distances (cost distances). The scaling factor increases with lower bicycle suitability scores. The shortest route between origins and destinations is then calculated on the network with the scaled distances. They further use square footage of the commercial destinations to model the attractiveness of destinations. Thus, locations with close destinations, routes to destinations with a high bicycle suitability and a high attractiveness of destinations have high bikeability index values (Lowry et al., 2012; Schmid-Querg et al., 2021). In the same manner, Wysling and Purves (2022) calculate a bikeability index on a regular grid with a cell size of 250 x 250 meters for Paris, France. The perceived distances used in the gravity-based accessibility calculation are scaled depending on the cycling infrastructure type, the maximum speed for motorized traffic, and the slope along network segments. In comparison to the bikeability index developed by Lowry et al. (2012), their index does not focus on accessibility to one destination type. The index considers a variety of destinations of the types leisure, education, city function, shopping and public transport. Focusing not only on one specific destination type better captures the general traffic coverage quality.

The only gravity-based bikeability index developed so far in Switzerland is the one by Grigore et al. (2019). Their index describes bikeability to jobs and the main train station for a case study area in the city of Basel. It focuses on commuter cyclists. Cycling quality factors considered in the study are the slope, the type and dimension of cycling infrastructure, additional hazards (such as car parking) and green and aquatic areas along streets. Additionally, they model the cycling quality of intersections using factors such as signalization, type of turn and average daily traffic. However, the study is limited to a relatively small case study area. Some data are not commonly available and are restricted to the case study area Basel. Data on some aspects of cycling quality, like intersections, further had to be introduced manually. These factors limit the applicability and reproducibility of the index to potentially any or larger case study areas in Switzerland.

2.4.3 Comparison between cities

As the mentioned studies in the previous paragraphs have shown, studies concerned with the modeling of bikeability are usually restricted to one specific city (Codina et al., 2022; Grigore et al., 2019; Krenn et al., 2015; Winters et al., 2013). These studies allow to investigate how bikeability varies within a city. Comparisons of bikeability between different cities are not made, mainly because their methods are not fully reproducible and applicable to other cities. Winters et al. (2016) address this research gap with the comparison of Bike Score between different cities in the USA and Canada. Bike Score is an additive bikeability index, calculated at census tract level using environmental attributes associated with cycling: Topography, road connectivity, desirable amenities, and density and quality of bike infrastructure. Winters et al. (2016) can calculate the index for 24 different North American cities. The values of the bikeability index at census tract level are averaged to one single figure for each city, allowing to compare bikeability between cities. The study concludes that Bike Score is positively associated with the bike modal share for trips to work at the census tract level and the city level.

Otherwise, approaches aiming to compare how strongly cities support the decision to cycle are mostly based on the concept of bike friendliness and not bikeability. In addition to bikeability of a city, they further consider factors such as laws and cycling education. The comparison is only based on one single figure for each city. How the distribution of values looks like within a city is not known. The Copenhagenize Index ranks the most bicycle-friendly cities in the world (Copenhagenize, 2019). Based on a data evaluation, it scores cities by considering 14 different categories and giving bonus points for special efforts. The categories of the total index range from bicycle infrastructure, over lobbying of NGOs to political involvement in promoting bikeability.

In contrast to the Copenhagenize Index, most studies aiming to compare bike friendliness between different cities are not based on the analysis of spatial data, but on surveys among the population. In Switzerland, the "Prix Velo" ranks Swiss cities depending on their bike friendliness every four years (Pro Velo Schweiz, 2022). In an online survey, people can give scores in different subcategories: Safety, comfort, bike network, parking facilities, priority and traffic climate. The scores of the different subcategories are aggregated into one final score, which is used to build the city ranking.

2.5 Research gaps

The literature review has unveiled the following research gaps:

- A fully reproducible bikeability index allowing to describe the traffic coverage quality by bike is missing so far for urban areas in Switzerland.
- Most of the studies aiming to compare how well a city is suited for cycling assess bike friendliness based on surveys and not bikeability using geospatial data. They provide one single figure for each city, not allowing to investigate the variation of bikeability within a city.
- To the best of the author's knowledge, a study comparing both bikeability within a city and between different cities using a gravity-based bikeability index with perceived distances is lacking so far.

To address these research gaps, this project aims to construct a gravity-based bikeability index for different Swiss cities. The developed index enables to investigate within- and between-city variation of traffic coverage quality by bike for home-based trips with a utilitarian purpose. The approach and reliance on publicly available data ensure reproducibility to potentially any urban area in Switzerland. In addition, the results should show where people are relatively deprived of suitable bike infrastructure to reach important destinations. To locate populated areas comparably most in need of improvements to the bicycle infrastructure, the influence of bike infrastructure on the accessibility to reachable destinations will be isolated. As stated in Section 1.2, addressing the research gaps this thesis is built around the following research questions:

- **RQ1**: How does the level of bikeability compare within and between different Swiss cities?
- **RQ2**: Which areas are comparably most in need of improvements to the bicycle infrastructure?

3 Case study areas and data

In this chapter, the case study areas and the data used for this project are introduced. The bikeability index developed in this thesis should be applicable and reproducible for any urban area in Switzerland to measure traffic coverage quality by bike for locations of residence. However, four of the most populated Swiss cities have been selected as the case study areas of this work: Zurich, Bern, Winterthur and Lausanne. Section 3.1 presents the role of bike traffic, the recently put in place national law to promote cycling, and common bike infrastructure types in Switzerland. It further illustrates the four case study areas and why they have been selected. This background information will be useful for some steps in the methodology and the discussion of the results in the following chapters. The data used for this thesis and the reasoning behind their selection are described in Section 3.2.

3.1 Case study areas

3.1.1 Cycling in Switzerland

The most recent Swiss micro census of mobility shows that in the last years and particularly during the COVID-19 pandemic, cycling has gained popularity as a mode of transport (BFS and ARE, 2023). Between 1994 and 2010 the cycling modal share has steadily decreased, but since 2010 it has increased again. Nevertheless, in 2021 37% of all trips by the Swiss population were done by motorized private traffic, and only 6% by bike. Table 1 breaks down how the average distance traveled and the average travel time per day are distributed across the various modes of transport. Of the 30 km that a Swiss person travels on average per day, 21.1 km are covered by private motorized transport, 5.9 km by public transport, 1.6 km by foot and 0.9 km by bicycle. These 0.9 km covered by bike equal to a share of daily mean distance of 3.1%. In 2010, the share was 2.1%. For home-based trips with a distance between 3.1 and 5 km, which can be considered as well suited for the use of bikes, the car is the main mode of transport: 38% of all trips are covered by car, 32% by foot, 17% by bike and 10% by public transport (BFS and ARE, 2023). It should be noted that the values for the year 2021 are to some degree influenced by the COVID-19 pandemic. For example, whereas the mean distance traveled by a Swiss person was 30 km in 2021, it was 36.8 km in 2015.

Table 1 Average daily distance and travel time per person for different modes of transport in Switzerland. Source: BFS and ARE (2023).

Mode of transport	Daily distance [km]	Daily travel time [min.]
Foot	1.6	30.0
Bike	0.9	5.0
Motorized private transport	21.1	30.1
Public transport	5.9	8.0
Rest	0.4	1.6
Total	30.0	74.6

In comparison to other European countries, Switzerland is in the middle of the field in terms of the amount of bike traffic (UVEK, 2018). Goel et al. (2022) compare the trip-based modal share of cycling (percentage of trips covered by bike) for urban areas in different countries and for different cities. They report a cycling modal share for urban areas in Switzerland of 6.7%, compared to 2.1% in England. However, in comparison to the Netherlands (26.8%) the cycling modal share is small. A comparison on the city-level shows that even the Swiss cities with the highest cycling modal share Basel (17%) and Bern and Winterthur (15%) are far below bicycle friendly cities such as in the Netherlands (Amsterdam: 36%, Groningen: 49%), Germany (Münster: 39%) and Cambridge (30%) in England (Buehler and Pucher, 2021; Stadtrat von Zürich, 2021).

The international comparison and the low figures of bike traffic, particularly for distances well suited for the use of bikes, indicate the so far unused potential of bike traffic in Switzerland. Swiss transport policy has been striving for several years to increase the share of bike traffic, increasing the relevance of cycling in transport and spatial planning (ASTRA, 2023a). A milestone for the promotion of bike traffic in Switzerland is the national law on cycle paths, in place since the 1st of January 2023 (Fedlex, 2022). It is intended to ensure that cycling is safe and convenient for the broad public in Switzerland. Until the end of the year 2042 the Swiss Federation, its cantons and municipalities must plan and build cycle networks. The law defines cycle path networks as "connected and continuous traffic routes for cyclists with the corresponding infrastructure" (Fedlex, 2022). It stipulates that there should be two types of cycle path networks: One for leisure time and one for daily trips with a utilitarian purpose.

While cycle path networks for leisure time mostly serve recreation and are located outside of settlement areas, cycle path networks for daily life are mainly located within and between settlement areas. According to the law, cycle path networks include the following infrastructure types: Streets, streets with cycle lanes, cycle paths, cycle tracks, paths, parking facilities and similar types. Cycle path networks for daily life to serve utilitarian trips are defined as follows: "In particular, they provide access to and connect residential areas, workplaces, schools, public transport stations, public facilities, stores, leisure and sports facilities as well as cycle path networks for recreational purposes" (Fedlex, 2022).

The law further regulates the construction, preservation and planning principles of the networks. The planning principles include that the network segments should be coherent and continuous, particularly to locations mentioned in the definition of the networks. However, the type of bike infrastructure is not given and as mentioned in the paragraph above, streets without any particular bike infrastructure can also be part of the networks. Authorities should ensure that the network segments are safe, and that bike traffic is separated from pedestrians and motorized traffic, where it is feasible and appropriate. The networks should further have an appropriate density with direct route guidance (Fedlex, 2022).

3.1.2 Main bike infrastructure types

As stated in Section 2.2, the most important factor determining cycling uptake is the perceived safety among the population. Perceived safety is heavily influenced by the degree of separation from motorized traffic and its speed. Figure 4 displays the results of a survey among Swiss people commuting by bike concerning perceived safety (Rérat et al., 2019). It shows the percentages of respondents that feel safe for different degrees of separation from motorized traffic and speed limits. The higher the speed limit and the lower the degree of separation from motorized traffic, the less cyclists feel safe. 81% of the respondents feel very safe on cycle tracks physically separated from motorized traffic, whereas only 26% feel very safe on streets with a speed limit of 50 km/h and a cycle lane. As the survey was conducted among participants of the initiative "bike to work", targeted to commuters by bike, it is expected that for the whole population (including less experienced cyclists, children, or elderly people) the perceived safety differences would be larger.

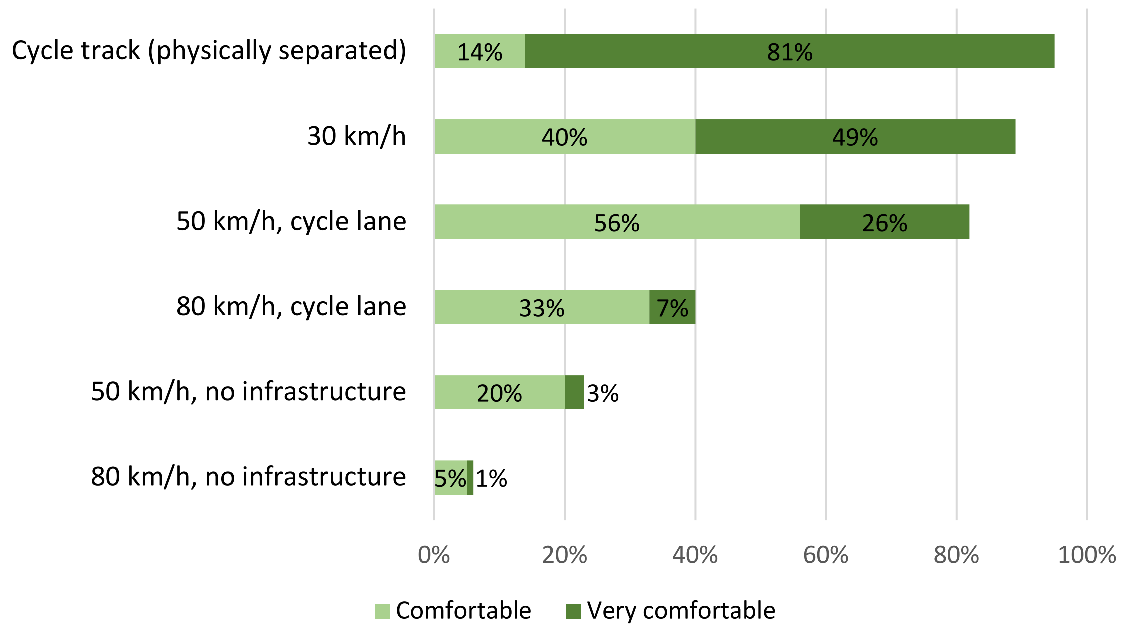


Figure 4 Perceived safety for different types of bike infrastructures. Illustration adapted from Rérat et al. (2019).

Rérat et al. (2019) distinguish between three types of street bike infrastructure: No infrastructure, cycle lanes and cycle tracks. Exemplary cycle lanes and cycle tracks for Switzerland are shown in Figure 5. Cycle lanes consist of a yellow marking on streets to reserve a certain width of the streets for cyclists. They are primarily implemented on streets with a speed limit above 30 km/h. The perceived safety for cycle lanes is not as high as for separate bike infrastructures since the separation is just optical. In Switzerland, a cycle lane width of 1.5 meters is recommended. Nevertheless, it is acknowledged that wider cycle lanes are perceived as safer (Rérat et al., 2023).

Cycle tracks are physically separated from the street, for example, by a grass strip or a curb. They are mostly present along streets with high speed limits or very high traffic volumes. Cycle tracks fulfill the desire of both less and more experienced cyclists (Rérat et al., 2023). In countries with a high cycling modal share and low bike accident rates such as the Netherlands, cycle tracks are overall the main type of bike infrastructure (UVEK, 2018). On the contrary, in Switzerland, the most frequently used infrastructure types are cycle lanes or mixed traffic with motorized traffic or pedestrians (UVEK, 2018).

Figure 5 Cycle lane (left) and cycle track (right). Illustrations by Rérat et al. (2023).

Other exemplary types of street infrastructures for bikes not covered in the survey by Rérat et al. (2019) are shown in Figure 6. When a bike pictogram is present on a bus lane, cyclists are allowed to use the lane too. As with cycle lanes, there is no physical separation from motorized traffic, but the lane is wider. Shared bus lanes should only be installed when they are wide enough to allow for safe overtaking by buses. The challenge for the coexistence of buses and bikes is smaller when the amount of bus traffic is small and the shared section is short (Rérat et al., 2023). An infrastructure type not present in city centers, but rather on the outskirts of urban municipalities or in rural areas leading through forests or fields are tracks. Tracks mostly have the width of one single motorized traffic lane. They have a very low motorized traffic volume, because usage is usually restricted to delivery or agricultural vehicles. Therefore, they provide a high sense of safety to bicyclists (Rérat et al., 2023).

Figure 6 Bus lanes with cyclists allowed (left) and tracks (right). Illustrations by Rérat et al. (2023).

On paths for pedestrians or footways, bikes may or may not be allowed. If bikes are allowed, there are two main layouts for the coexistence of bikes and pedestrians. There is either mixed usage without any separate traffic area, or there is a separate area for bikes and pedestrians (by a centerline or physical separation). Mixed-use paths provide a relatively high perception of safety for cyclists, particularly compared to street sections with a high speed limit, high traffic volume and a short width. But especially with a high volume of pedestrians, cyclists find it more convenient to ride on elements separated from pedestrians. Areas shared between cyclists and pedestrians further shift the danger to pedestrians (Rérat et al., 2023). If not signalized differently, the riding of bikes in pedestrian zones or on sidewalks is prohibited (except for children under 12 years of age). Pedestrian zones, where the riding of bikes is explicitly allowed, are not well suited as a main component of a bike network as pedestrians have the right of way. Nevertheless, with the prohibition of motorized traffic, they provide relatively safe accessibility to stores in the city center, where pedestrian zones are mainly located (Rérat et al., 2023).

As the speed regime also affects the perception of safety, some infrastructure measures do not deal with physical infrastructures, but traffic calming measures. On residential streets, the maximum speed is increasingly often restricted to 30 km/h. They normally do not have infrastructure types like cycle lanes. One-way streets with such a speed regime may allow oncoming bike traffic, potentially with an installed cycle lane. Through the reduction of the speed difference between cyclists and motorized traffic, such traffic calming zones increase the safety for cyclists compared to higher speed regimes. Nevertheless, without separate bike infrastructure and depending on the amount of motorized traffic, the added safety is limited (Rérat et al., 2023). Special cases of 30 km/h streets are cycle streets (Rérat et al., 2023). They have the same speed regime, but the right of way is suspended. Cycle streets have a designated priority to cyclists over cars, but without any dedicated bike infrastructure (von Stülpnagel et al., 2022). They increase the comfort for cyclists and the continuity of the bike network. Shared zones have the lowest speed limits. The speed limit for vehicles is 20 km/h and pedestrians have the right of way. No special bicycle traffic facilities are provided in shared zones (Rérat et al., 2023).

3.1.3 Case study areas

The cities Zurich, Bern, Winterthur and Lausanne are the case study areas of this project. Whereas Lausanne is in the French speaking part, the other three cities are in the Swiss German speaking part of Switzerland. Zurich and Winterthur are part of the canton of Zurich, Lausanne belongs to the canton of Vaud. Bern is the biggest city in the canton of Bern and is further the federal capital. All four cities belong to the most populated ones in Switzerland, with at least 100’000 inhabitants. In contrast to Bern, Winterthur and Zurich, Lausanne consists of two parts separated from each other. The exclave of Vernand is separated from the rest of the municipality by Romanel-sur-Lausanne and Le Mont-sur-Lausanne. Figures 7-10 show aerial images with the main roads and a multidirectional hillshade in the background of the four case study areas. The geographical names on the maps were used from the Federal Office of Topography (swisstopo), and some were manually introduced. They provide the geographical context with neighborhoods and micro toponyms mentioned in the presentation of the results in Section 5.

Figure 7 Map of the municipality of Lausanne with the main road network and geographical names. Maps adapted from swisstopo.

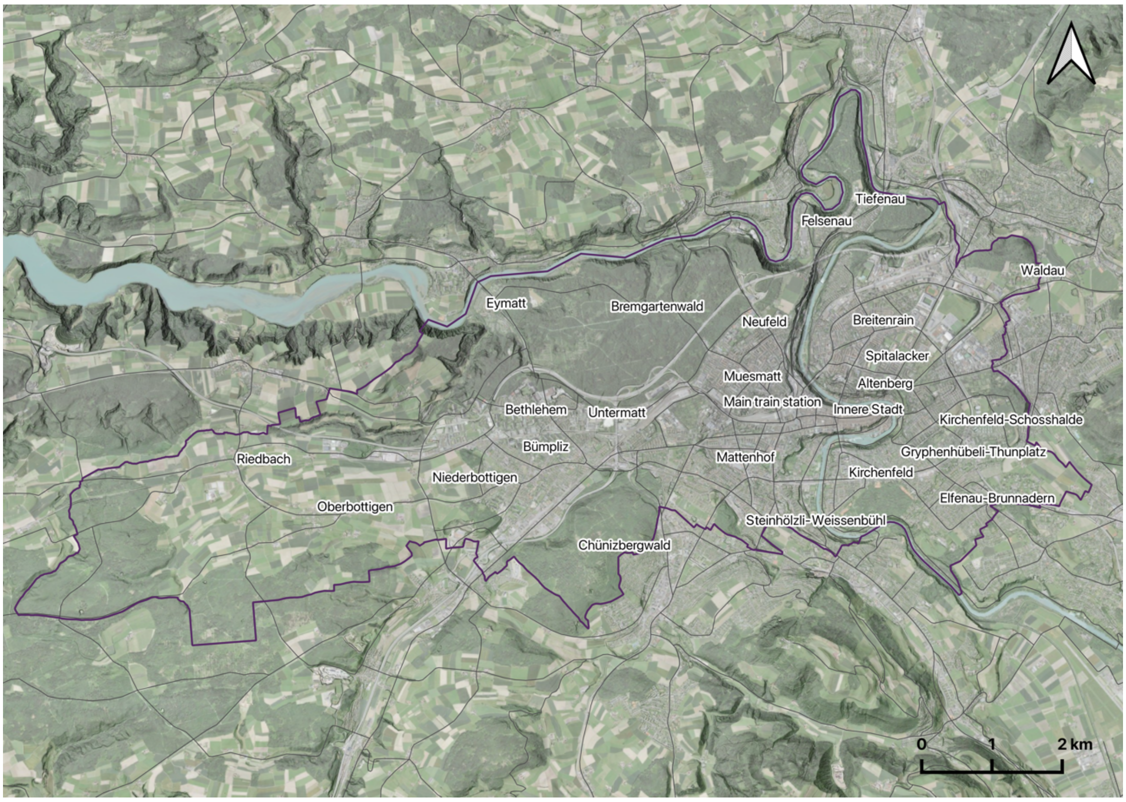


Figure 8 Map of the municipality of Bern with the main road network and geographical names. Maps adapted from swisstopo.

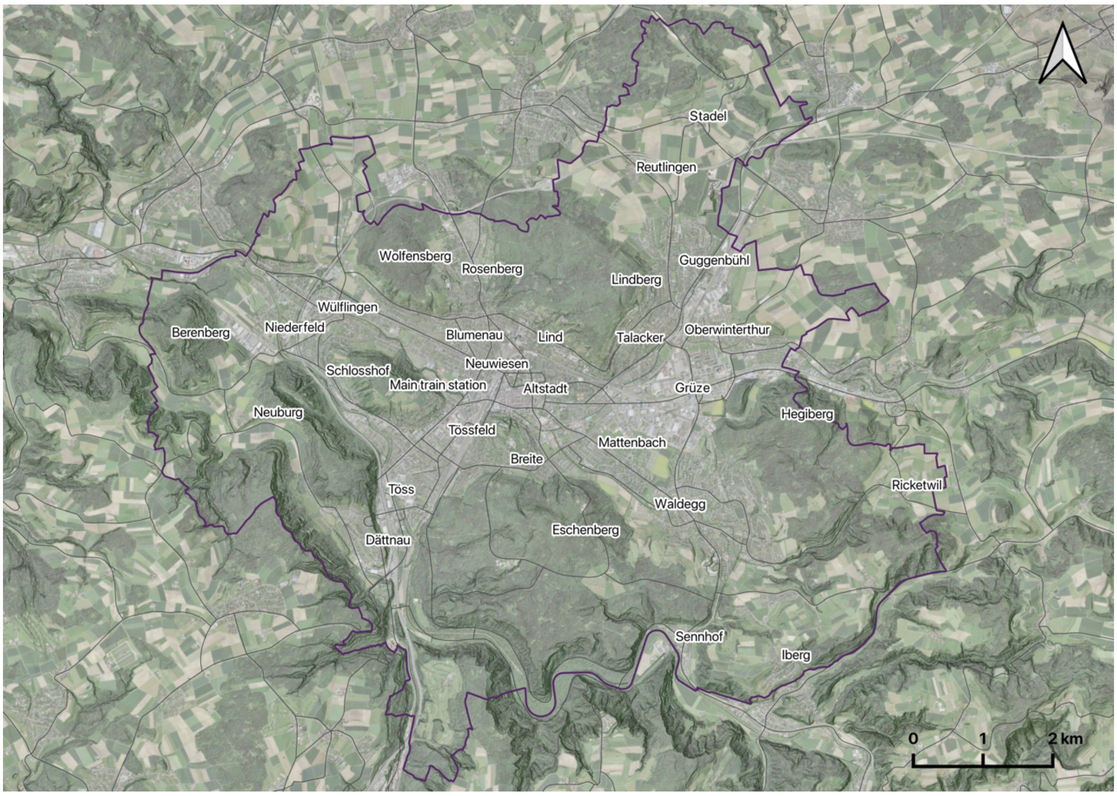


Figure 9 Map of the municipality of Winterthur with the main road network and geographical names. Maps adapted from swisstopo.

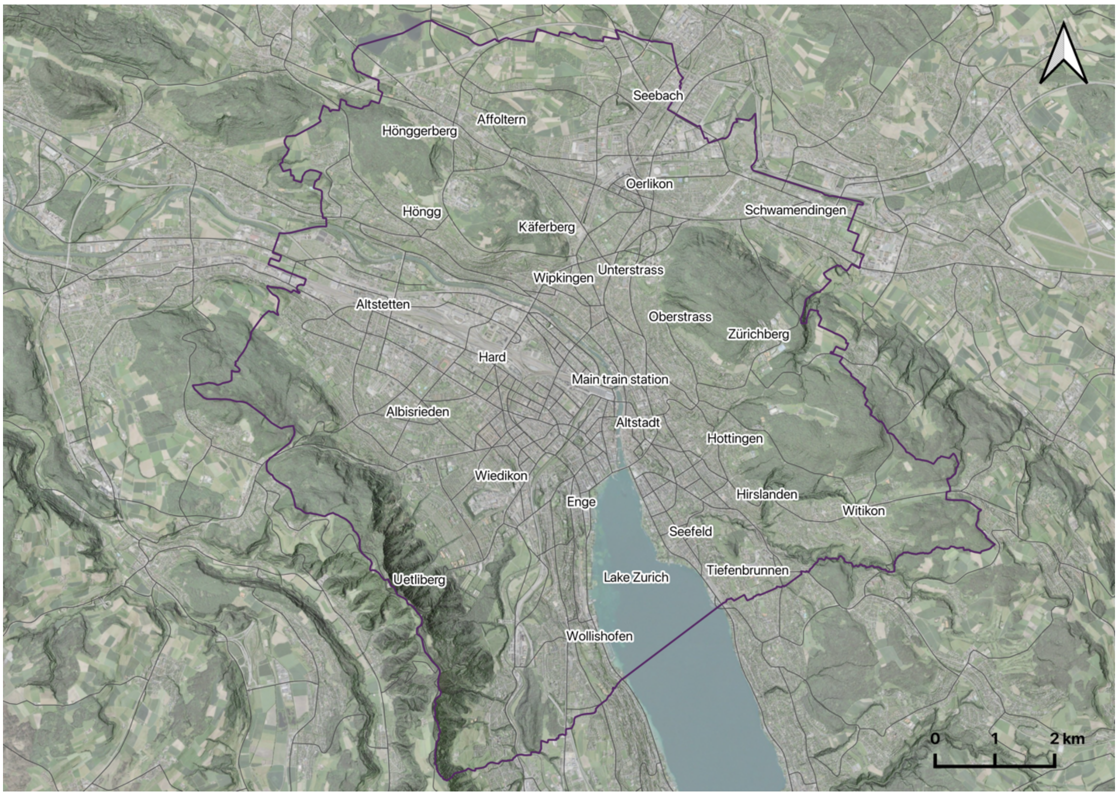


Figure 10 Map of the municipality of Zurich with the main road network and geographical names. Maps adapted from swisstopo.

Table 2 gives an overview of the population size, the area, the population density and the cycling modal share for the four case study areas. The trip-based bike modal share (relevant is the main mode of transport per trip) is the highest in Bern with 16%. Winterthur has a bike modal share of 15% and Zurich a share of 13% (Städtekonferenz Mobilität et al., 2023). The share is the lowest in Lausanne with 2% (Ville de Lausanne, 2023a). However, it is important to note that the most recent data for Lausanne are from 2015, whereas they are from 2021 for the other three cities. In 2015, the share was 15% in Bern and Winterthur and 12% in Zurich (Basel-Stadt et al., 2017).

Table 2 Population size, area, population density and trip-based bike modal share (relevant is the main mode of transport per trip) for all four case study areas. Sources: Städtekonferenz Mobilität et al. (2023) and Ville de Lausanne (2023a).

	Population size 2022	**Area [km²]**	**Population density (per km²)**	**Trip-based bike modal share 2021 [%]**
Bern	134’671	51.6	2’610	16
Lausanne	141’753	41.4	3’424	2 (2015)
Winterthur	117’045	68.1	1’719	15
Zurich	428’180	87.9	4’871	13

The mentioned four cities have been selected as the case study areas of this thesis since it is expected that the level of bikeability is quite different between them. Pro Velo Schweiz (2022) conducts a survey among the population every four years and based on the results scores the bike friendliness of Swiss cities. The possible scores range from the lowest score of 1.0 to the highest score of 6.0. Scores below 4.0 are defined as insufficient and above as sufficient. Table 3 depicts the ranking for the biggest cities in Switzerland (more than 100’000 inhabitants). Winterthur and Bern are evaluated as sufficient, whereas Lausanne and Zurich have scores below 4.0. The study therefore looks at two cities at the top of the ranking (Bern and Winterthur) and two cities at the bottom of the ranking (Lausanne and Zurich).

Table 3 “Prix Velo” city ranking. Source: Pro Velo Schweiz (2022).

Rank	City	Mark	Overall rank
1	Winterthur	4.4	3
2	Bern	4.1	9
3	Basel	4.0	11
4	Geneva	3.7	29
5	Lausanne	3.7	29
6	Zurich	3.4	45

Most Swiss cities have already started to promote bike traffic before the national law on cycle paths was put in place (UVEK, 2018). In some cities, the ambitions have further increased with several city-level initiatives during the last few years, including the implementation of bike infrastructure (UVEK, 2018). This is also true for the four case study areas of this thesis (Stadt Winterthur, 2023; Stadtrat von Zürich, 2021; TVS, 2015; Ville de Lausanne, 2023a). The city of Zurich, for example, has launched the “Velostrategie 2030” (Stadtrat von Zürich, 2021). The vision of the strategy is to make cycling safe and convenient for the whole population. The strategy includes safety and behavioral campaigns, anchoring the promotion of cycling in all planning stages, adapted speeds and the creation of a safe and visible network of cycle routes. The infrastructure measures include interventions such as eliminating weak points in the network, implementing right turns on red and making roadworks bike friendly. However, the focus is on priority routes for bicycles as a new element in the network. They should offer the highest quality in terms of safety, comfort and flow, and connect the different districts. The traffic regimes for priority routes can be different, but all should favor bicycle traffic on these routes. They are primarily implemented on low-traffic residential streets and should enable overtaking and passing each other (Stadt Zürich, 2021). In addition, the bicycle standards regulating the implementation of bicycle infrastructure in the city will be adapted. Until now, physically separated cycle tracks have only been installed in exceptional situations. In the future, however, the urban bike network should consist of more such connections (Metzler, 2023).

In contrast, the cities of Lausanne and Bern formulate a specific target for the bike modal split. The city of Lausanne wants to increase the trip-based bike modal share from 2% in 2015 to 15% by 2030 (Ville de Lausanne, 2023a). In the city of Bern, the proportion of bike trips by the city's population should be 20% by 2030 (TVS, 2015). The city of Bern is to become the cycling capital of Switzerland. One focus of the campaign lies on the cycling infrastructure. Safe and attractive cycle routes and sufficient parking facilities are to be created. A good cycling infrastructure is the basic prerequisite for encouraging more people to cycle. However, other key areas of action such as the promotion of cycling among children, the promotion of cycling culture and the involvement of the population are also defined in the cycling campaign (TVS, 2015).

3.2 Data

This thesis aims to develop a bikeability index for four different case study areas, the cities of Zurich, Winterthur, Lausanne and Bern. Additionally, the index should be fully reproducible for any urban area in Switzerland to describe traffic coverage quality by bike. To ensure reproducibility, the goal was to completely rely on publicly available data with nationwide coverage, even though for one case study area a more suitable dataset might have been available. Where it was possible and suited Open Government Data (OGD) have been used, otherwise data from OpenStreetMap (OSM) have been considered. The following paragraphs describe the different data sources used and the reason for their selection. An overview of the data used for the analysis is provided in Appendix A.

The central element of the analysis is a routable bike network with information on the type of bike infrastructure. Therefore, data including all types of infrastructures on which cycling is possible and allowed with additional information on the type of bike infrastructure present are required. For these data, OSM was chosen as the data source. OSM provides a digital map of the earth and its underlying data free to use (Haklay, 2010). The information it provides is often referred to as volunteered geographic information (VGI). The geodata can be collaboratively collected by individuals on a voluntary basis (Neis and Zielstra, 2014; Goodchild, 2007). Any registered person is part of the community and can add, modify or delete information in the OSM database. However, OGD can also be imported into OSM, if the data license allows it (OpenStreetMap Wiki, 2023). The database is continuously updated and provides the latest data ready to download (Girres and Touya, 2010). OSM data are used in a variety of fields such as urban planning, mapping or routing applications (Hahmann et al., 2018; Neis and Zielstra, 2014).

To create a feature in the OSM database representing an object from the real world, three different types of objects can be used: Nodes, ways and relations (Touya et al., 2017). With tags, consisting of a key-value pair, attribute information can be added to each object. They are free-format textual fields (Hochmair et al., 2015). A street section might, for example, be tagged with *highway=primary*, *maxspeed=50* and *cycleway=lane*. A contributor is free to suggest or use a new tag as attribute information. The open tagging system indicates that tagging is not enforced (Haklay and Weber, 2008). The same feature might therefore be tagged differently depending on the user (Hochmair et al., 2015). In practice, however, tagging conventions with suggested key-value pairs for a large variety of characteristics are widely used in the community. Recommended and widely used key-value combinations are provided in a wiki (OpenStreetMap Wiki, 2023). Taginfo (OpenStreetMap Taginfo, 2023) further provides statistics of the tags present in the OSM database to describe a certain feature. The tagging conventions are, for example, influenced by map render engines, which use specific rendering functions that consider only certain features and tags for the mapping. Thus, a certain degree of standardization is introduced to the description of objects in OSM (Neis and Zielstra, 2014).

Because of the data collection process, many studies investigate the quality of OSM data. According to the International Organization for Standardization (ISO), the quality of geodata is comprised of five components: Completeness, logical consistency, positional accuracy, temporal accuracy and thematic accuracy (ISO, 2013). The assessment of data quality is usually based on a comparison between OSM data and administrative or commercial data (Haklay, 2010). Previous studies found that the data quality of OSM in Western Europe is high (Graser et al., 2014). Some studies even found that OSM is more timely than administrative data (Ferster et al., 2020; Nelson et al., 2021). A few studies specifically assessed data quality of bike network and bike infrastructure data (Ferster et al., 2020; Hochmair et al., 2015). OSM is found to be a valuable data source for non-motorized transport like cycling. Especially for multicity studies dealing with bike infrastructure the use of OSM is encouraged (Ferster et al., 2020).

Before OSM has been selected as the source for the needed bike network and bike infrastructure data, data provided by the Federal Office of Topography (swisstopo) have been evaluated. With swissTLM3D swisstopo (2023e) provides a dataset of streets and paths in Switzerland. It contains information such as the width and the surface type of streets. However, no information is given on the type of bike infrastructure present on a street or the maximum speed for motorized traffic. In contrast, with OSM tags that are frequently used detailed information is provided, for example, on the type of bike infrastructure, the speed limit, or if cyclists are separated from pedestrians on a path. Since such information is important for the analysis, it was decided to work with OSM data instead of OGD.

To get the OSM bike network/infrastructure data, the latest PBF file for Switzerland provided on the third-party website Geofabrik (2023) was downloaded. The file contains all OSM data up to 5.5.2023. PBF files are compressed versions of the usual .osm files. Using the software osm2pgsql the data were imported into a PostgreSQL database. This approach comes with the advantage that for the import, the OSM tags that are needed for the analysis and should therefore be included as attributes in the database can be defined in a custom style file. For the bike network/infrastructure data, the tags that are also used for the rendering of CyclOSM[1], a bicycle-oriented map displaying bike infrastructures built on top of OSM data, were used. The part of the used style file defining which tags should be imported for the bike network/infrastructure data can be found in Appendix B. The imported tags were used as attributes for the analysis of the bike network described in Chapter 4. A separate table is created in the database for each object type – points, lines and polygons. Data relevant for the bike network/infrastructure are in the line table. Since the table contains all OSM line features and not just line features relevant for bike routing, the data had to be further preprocessed. The preprocessing steps to get a routable bike network are described in Section 4.2.

The routable bicycle network derived from the OSM data with information on the bike infrastructure and speed limit forms the basis of the analysis. It was further supplemented with additional attributes that have been identified to influence cyclists' travel behavior: The slope and the natural environment. All characteristics together were used to calculate

[1] Available at: https://cyclosm.org/

perceived distances for the gravity-based bikeability approach. The sensitivity analysis with bike accidents described in Section 4.4.4 was based on reported traffic accidents provided as point data (ASTRA, 2023b).

To model the slope of the segments in the bike network, a digital elevation model (DEM) with a resolution of 2 meters provided by swisstopo (2023b) was used. Since the modeled slopes should be accurate, the raster with a resolution of 2 meters was preferred to the DEM with a resolution of 25 meters, also provided by swisstopo (2023a). To enrich the elevation data from the DEM, swissSURFACE3D (swisstopo, 2023d) has additionally been used. This dataset contains classified LiDAR data points, describing the surface of Switzerland, and not just the terrain. On average, one square meter contains between 15 and 20 LiDAR data points.

For the natural environment, green and aquatic areas have been extracted from OSM since in comparison to the data alternative by swisstopo, smaller green and aquatic areas such as parks in the cities are additionally included. To get green areas, the OSM data was filtered for polygons with OSM key-value pairs provided by Novack et al. (2018). For aquatic areas, the dataset was filtered for objects with a *landuse=water* tag. Rivers and lakes were therefore included, minor waterbodies like small waterways were not assumed to be important for cycling quality. In Appendix B, the style file used for the import of green and aquatic areas into the PostgreSQL database can be found. The green and aquatic areas are imported into the polygon table in the database. To consider trees and not only areas along the bike network in Switzerland, swissTLM3D (swisstopo, 2023e) has been used as an additional data source. It provides trees in Switzerland as point data.

The bikeability index was calculated on the STATPOP dataset (BFS, 2023a), a raster with all populated hectare raster cells in Switzerland. The centroids of these raster cells were used as origins in the bikeability calculation. Points of interest (POIs), which act as destinations in the gravity-based bikeability calculation, were mainly included based on areas provided in the swissTLM3D (swisstopo, 2023e) dataset as polygons. The dataset includes plots with special land usage such as areas with schools, hospitals, or leisure and sports facilities. Since the swissTLM3D dataset does not include grocery stores, OSM has been used for this destination type. A dataset with train stations as point data was provided by the Federal Office of Transport (BAV, 2023b). For the filtering of all data to the respective municipality boundaries, the swissBOUNDARIES3D dataset provided by swisstopo (2023c) was used.

4 Methodology

Addressing the research questions outlined in Section 1.2, the goal was to develop a gravity-based bikeability index for the four cities Bern, Lausanne, Winterthur and Zurich (compare Section 3.1.3). The identification and quantification of the different factors included in the index by analyzing GPS data to model cyclists' behavior was beyond the scope of this project. In contrast, the inclusion and operationalization of the different factors relied on existing literature as good as possible. Section 4.1 introduces the aspects of graph theory and network analysis relevant for the proposed methodology. In Section 4.2, it is explained how the downloaded OSM data were preprocessed to get a routable bike network for the further analysis. In the next step (Section 4.3), the bicycle suitability of the segments in the network was modeled. Factors included in the bicycle suitability assessment were bicycle level of service (considering the type of bike infrastructure and speed limit), the slope, and green and aquatic areas. For each factor, a multiplier was defined to calculate perceived distances. These perceived distances were then used to calculate the gravity-based bikeability index (see Section 4.4). Finally, Section 4.5 introduces a measure to isolate the effect of bike infrastructure on bikeability.

To make the developed methodology reproducible for potentially any urban area in Switzerland, the programming language R was used as the main software for the workflow. R Markdown scripts were written for the four case study areas. The scripts are available on Github: https://github.com/nmaian/Model_bikeability. With some minor adaptions, particularly for the data inputs, the scripts should be easily applicable to other urban areas in Switzerland. The preprocessing of the data, the analysis and to some degree the visualizations were executed in R. To produce the final bikeability maps, QGIS was additionally used.

4.1 Network analysis

Bikeability assessments using spatial data usually revolve around the analysis of bike networks. Transport networks are a common representation of transport systems (Barthélemy, 2011). They are graphs with attributes for edges and vertices (nodes). As transport systems have a spatial reference, edges and vertices of transport networks are associated with spatial attributes (geometries). With the simplest and most frequently used type of representation for street networks, vertices represent intersections, and edges connecting the vertices represent street segments (Kurant and Thiran, 2006). In the case of street networks, the characteristics of a street segment are associated with the corresponding edge and intersection characteristics with the corresponding node in the graph (Grigore et al., 2019; Winters et al., 2013; Wysling, 2021). Typically, vertices connect at least three edges, corresponding to street junctions (Gilardi et al., 2020). However, they can also be pseudo-nodes, connecting only two edges (Hassan and Hogg, 1987). For example, pseudo-nodes can be used to further subdivide an edge at locations where an attribute of a street changes. As the nodes and edges of a graph have geometries as an attribute, they are mostly associated with point and line features respectively (Gilardi et al., 2020).

Graphs can have different topological properties. If from every node in a graph every other node can be reached, the graph is connected. A graph consisting of sub-components not connected is called to be disconnected. Planar graphs have a node at every point where two edges intersect. With non-planar graphs, in contrast, edges are allowed to cross each other without a node at the point of intersection. Examples of such a case are edges representing an under- or overpassing street (bridges or tunnels), which do not form a junction. Graphs can further be directed or undirected. In directed graphs, the direction of travel for an edge might be restricted (e.g., edges associated with one-way streets).

The mentioned properties of a graph are relevant for analysis tasks of transport networks widely used: Routing problems. One of the most fundamental problems for the analysis of transport networks is the computation of the optimal path (Kumari and Geethanjali, 2010). Given two points in the network, the goal is to find the path with the minimum cost between them. The path between a start and end point (origin and destination) can be optimized considering different criteria. For example, in a weighted network, where edges have numerical weights, the total costs/weights are optimized. Costs frequently used in routing analyses are travel distances, travel times or generalized costs (length of edges scaled by cost factors). For the computation of the shortest/optimal path, a variety of algorithms have been developed (Iqbal et al., 2018). The most well-known shortest path algorithm to solve one-to-one routing problems is Dijkstra's shortest path (Dijkstra, 1959).

The shortest paths in a network are further used for fundamental measures of the edges and nodes in a graph. Centrality measures indicate the importance of an edge or node (Marsden, 2005). The degree centrality of a node is the number of edges the node connects. Closeness centrality is the longest shortest path for each node. For betweenness centrality, the shortest path between all pairs of nodes is calculated. Betweenness centrality indicates how many shortest paths go through a particular edge or node.

4.2 Preprocessing bike network

To preprocess the bike network data, the OSM line feature data were first imported into R from the PostgreSQL database (compare Section 3.2). The line feature OSM dataset was then cropped to the respective municipality boundary for Zurich, Winterthur and Bern. Since the municipality of Lausanne consists of two parts separated from each other and to avoid that these parts are disconnected in the later route calculations, for Lausanne the bounding box of the municipality was used to crop the data (see Figure 7 in Section 3.1.3). Based on the line features an undirected sfnetwork was created. To ensure topological correctness, i.e., correct degree centrality of the nodes in the network, the edges were subdivided at intersections. Since all original OSM line features (such as railways) were still included in the network, the next step was to filter the objects using the attributes (OSM tags) to get a routable bike network. For the filtering, it was assumed that if suitable bike infrastructure is present, cyclists will follow the rules. Hence, the network should consist of all street/path segments on which cycling is legally allowed and possible. Sidewalks for which bike traffic is not explicitly allowed (except for children below 12 years of age) were therefore, for example, excluded from the analysis. All present values of an attribute (OSM key) have been assessed using taginfo Switzerland, the OSM wiki, and visually in QGIS to decide if segments with such an attribute value should be considered for the bike network. The filtering criteria were defined based on the following OSM tags: *Highway*, *access*, *barriers*, *motorroad*, *ramp:bicycle*, *route*, *vehicle*, *bicycle* and *smoothness*.

The filtered networks consisted of rather short segments. To increase the computational efficiency of the later route calculations, pseudo-nodes in the networks were removed. A pseudo-node was removed, if the two segments it connects have the same value for all relevant attributes describing the type of bike infrastructure. Otherwise, the pseudo-node was kept. Multiple edges were removed to make the networks further topologically correct. To make the networks routable without any multiple disconnected components, the main component of each network was used as the final network. Since for all case study areas, the sub-components were very small and randomly distributed in the case study area, it seemed valid to just work with the main component for the rest of the analysis.

Finally, to minimize the risk of wrongly missing important connections in the network (incompleteness), the network was visually assessed for potential missing connections using Google Earth satellite images as a comparison. The focus of the assessment for plausibility lied on nodes with a degree centrality of one. It was checked if nodes do correctly have a degree centrality of one, or if an important connection to another node is missing in the network. A wrongly missing connection between two nodes could mainly be attributed to a street/path section completely missing in OSM or to undershooting edges (mainly because of the previous filtering of short footways or sidewalks). Where a relatively important connection was identified as missing, an edge was manually added to the network. However, the sanity check did not reveal many wrongly missing important connections in the network. Only a few edges had to be manually introduced.

For the later average slope calculations (see Section 4.3.2), the segments in the network should not be too long. In general, the segments were short, just some outliers had a length of a few 100 meters. Segments with a length above 400 meters were further subdivided into three parts of equal length.

4.3 Bicycle suitability

As stated in the literature review, a variety of factors are related to the route choice of cyclists. Bicycle suitability describes the comfort and perceived safety of a network segment to cycle on (Lowry et al., 2012). Under the consideration of measurable factors, segments get scored depending on their bicycle suitability. One score was given depending on the bike infrastructure and speed limit of a segment to assign a BLOS cost factor. A slope cost factor was defined using the absolute average slope of the network segments. The third bicycle suitability characteristic considered was the presence of green and aquatic areas surrounding network segments. A factor was assigned given the share of green and aquatic areas in the surroundings of a network segment. However, as green and aquatic areas have a positive influence on cyclists' route choice, the factor was treated as a benefit and not a cost factor. The two cost factors and the green and aquatic areas benefit factor were then combined to calculate perceived distances.

The bicycle suitability assessment was restricted to the three aforementioned characteristics, because they have been identified as significant in previous bikeability studies (Grigore et al., 2019; Iacono et al., 2010; Winters et al., 2013; Winters et al., 2010a; Wysling and Purves, 2022) and because for these factors data were publicly available. Bikeability indices should limit the number of characteristics and variables considered (Lin and Wei, 2018). They should be informative enough to show the main pattern, but also simple enough to facilitate reproducibility and interpretation for policymakers (Codina et al., 2022).

4.3.1 BLOS: Bike infrastructure and speed limit

The literature review and the survey among Swiss cyclists in Section 3.1.2 have revealed that the higher the speed difference to motorized transport on a road, the lower the perceived safety and comfort for cyclists. The speed limit can further be used as an approximation for traffic volumes, assuming that reduced speeds lower traffic volumes (Wysling and Purves, 2022). Lower traffic volumes in turn, positively affect cyclists' perceived safety and comfort. In all four case study areas, there are four different speed regimes on roads in the bike network: < 30 km/h, 30 km/h, 50 km/h and 60-80 km/h. For Switzerland in general, these are the main speed regimes on roads with cyclists allowed (i.e., excluding motorways). For all cities considered in this project, the coverage of the speed limit attribute is high for roads in the OSM dataset. Most network segments in the data without any speed limit given, are segments that do not have a speed limit, because motorized traffic is not allowed (i.e., paths). For the few road segments with a missing speed limit, a value was imputed. For each city, the highway types with a missing speed limit were determined. The mean speed limit of a highway type was then imputed for the segments of the same type with a missing value. This imputation was further assessed visually, conducting a comparison with maps provided by the different cities or with Google Street View. The imputation of the mean value of a highway type seemed to work reasonably well. However, for a few highway types in some cities the value to be imputed was changed based on the assessment of the segments with a missing value on the map applications considered.

The second factor used to define the bicycle level of service (BLOS) for a network segment was the type of bike infrastructure. In Section 2.3 and Section 3.1.2, it was highlighted that the perceived safety and comfort of cyclists increase with a higher degree of separation from other modes of transport. The different types of bike infrastructure in the four case study areas have been described in Section 3.1.2. Cyclists feel most safe with a devoted space physically separated from other modes of transport, primarily from motorized transport. On cycle paths, cyclists are physically separated from motorized transport and pedestrians. The same is true for cycle tracks, they lie, however, along road sections and their perceived safety is therefore further dependent on the speed limit of the road nearby. On footways, cyclists do not have to ride in mixed traffic with vehicles, but they must share the space with pedestrians. Cycle lanes with painted markings on the road provide less perceived safety compared to cycle tracks or cycle paths, because the separation from motorized traffic is not physical. The same is true for bus lanes with bike traffic allowed.

The types of bike infrastructure can be indicated by different attributes in the dataset (OSM keys). It might further have been the case that the same type of bike infrastructure is systematically tagged differently between the different cities. For example, it could have been that for Lausanne the values of a key are given in French instead of in English. Therefore, the values of all attributes in the dataset have been assessed for each city. However, there were not any different values assessed for the attributes relevant to determine the type of bike infrastructure. With nested if-else statements combining the different attributes for bike infrastructure, the type of infrastructure was determined for each network segment. For streets that provide a different type of bike infrastructure in the two directions of travel, the type of bike infrastructure leading to the higher BLOS was used. In addition to the types of bike infrastructure cycle street, cycleway, cycle track, footway, cycle lane and shared bus lane, two further infrastructure types have been introduced: Pedestrian zones and footpaths. Pedestrian zones where cycling was not explicitly allowed were separately introduced, because they are included in the bike network, even though as noted in Section 3.1.2 they prohibit riding a bike. They were included in the bike networks since they are important connections to destinations, and to avoid that the network gets broken in city centers, where pedestrian zones are located. They build a separate type and were not merged with the footway type to account for the fact that cyclists must dismount. The distinction will be important for the determination of the cost multiplier. Similarly, footpaths were not merged with footways. A visual assessment of footpaths in the case study areas revealed that the vast majority is located on the outskirts of the municipalities (e.g., in forests) and some of them have a surface impossible to ride a bike on. With the provided tags in OSM it was impossible to reliably distinguish if footpaths can be used by cyclists or not. Excluding footpaths completely from the networks would have led to many wrongly missing connections in the network. Treating footpaths separately allowed the introduction of another cost factor than for footways to account for the uncertainty of surface quality.

Given that all road segments in the network have a speed limit and all network segments have a bike infrastructure type associated, the two attributes could be combined to determine the cost multiplier and BLOS for each segment in the network. Table 4 presents the cost multipliers (c_{BLOS}) and levels of service depending on the speed limit and the infrastructure type. The cost multipliers were determined based on previous literature, mainly based on values presented in Broach et al. (2012), Grigore et al. (2019), and Wysling and Purves (2022). For multipliers greater than 1.0, the perceived length of a network segment is longer than its actual length. With a cost multiplier of 1.0 the two lengths are equal, and with a multiplier below 1.0 the perceived distance is shorter than the actual distance.

As in Wysling and Purves (2022), for road segments with a speed limit below 30 km/h the multiplier was set to 0.8. On these roads the speed difference between cyclists and vehicles is low and the traffic volume is assumed to be particularly low. On streets with a speed limit of 30 km/h, the speed difference and assumed traffic volume are higher, but they are still considered to be safe and comfortable. These street segments therefore received a multiplier of 1.0. An exception was made for cycle streets present on streets with such a speed limit. Cycle streets have a highly positive effect on cyclists' perceived safety (von Stülpnagel and Rintelen, 2024). Broach et al. (2012) quantify that cycling on cycle streets is equivalent to decreasing distance by almost 18%. Hence, they received a multiplier of 0.8.

For a speed limit above 30 km/h, a multiplier greater than 1.0 was defined. Streets with a speed limit of 50 km/h received a cost multiplier between 1.1 and 1.6, depending on the type of bike infrastructure present (cycle track, cycle lane/shared bus lane, no infrastructure). The higher the degree of separation from motorized traffic, the lower the multiplier. Broach et al. (2012) note that the variation in the type of infrastructure leads to changes in costs of 10-30%. For a speed limit above 50 km/h, the mentioned studies do not provide any cost factor. It was assumed that the multiplier for cycle tracks is the same as for cycle lanes and shared bus lanes in the lower speed category. Similarly, streets with cycle lanes or shared bus lanes received the same multiplier as 50 km/h streets without any bike infrastructure. Streets with a speed limit above 50 km/h and no bike infrastructure got the highest multiplier of 1.8.

Cycleways are bike infrastructures that are separately recorded and for which no speed limit was provided in OSM. It was therefore assumed that they are cycle paths, physically separating cyclists from vehicles and pedestrians. Based on the findings of Broach et al. (2012), a multiplier of 0.8 was used for this type of bike infrastructure. It was noted, however, that in all cities some cycle tracks are also separately captured as *highway=cycleway* with no speed limit of the road nearby, instead of as an attribute of the road. With the OSM tags available it was not possible to differentiate if a *highway=cycleway* segment is a cycle track (which should have a speed limit) or a cycle path, an issue also reported by Ferster et al. (2020). Footways are assumed to be of a neutral quality and therefore received a multiplier of 1.0 (Grigore et al., 2019). In practice, the perceived safety and collision risk with pedestrians is dependent on pedestrian traffic volume. Because such data are lacking, a constant cost factor was defined. For pedestrian zones and footpaths, a multiplier had to be assumed. Pedestrian zones are inconvenient for cyclists since they must dismount. As a penalty for this discomfort, a multiplier of 1.4 was assumed. To account for the uncertainty of the surface quality for footpaths in the data, a multiplier of 1.1 was defined. To each of the six different cost multipliers a bicycle level of service between A and F was assigned. The lowest multiplier corresponds to a BLOS of A, the highest multiplier to the lowest level of service of F.

Table 4 BLOS scores (A-F) and cost multipliers for different speed limits and infrastructure types.

Speed limit [km/h]	Infrastructure	BLOS	BLOS multiplier (c_{BLOS})
-	Cycleway	A	0.8
< 30	-	A	0.8
30	Cycle street	A	0.8
-	Footway	B	1.0
30	-	B	1.0
-	Footpath	C	1.1
50	Cycle track	C	1.1
-	Pedestrian zone	D	1.4
50	Cycle/bus lane	D	1.4
60-80	Cycle track	D	1.4
50	No	E	1.6
60-80	Cycle/bus lane	E	1.6
60-80	No	F	1.8

4.3.2 Slope

To model topography, the average slope for each segment in the network was calculated. Since the segments in the network are short, it seems reasonable to assume that the gradient on a segment does not vary considerably (the median segment length is the longest in Winterthur with 46.0 m). Broach et al. (2012) further find that a specification with the average slope of network segments performs better in cyclist route choice modeling than, for example, using the maximum slope. The calculation of the average slope was adapted from scripts by RPubs (2018) and Wysling and Purves (2022). First, using the DEM with a resolution of two meters the elevation for each start and end node of the segments in the network was determined. The elevation difference between the start and end node, together with the segment length was then used to calculate the absolute average slope in percentages for each network segment. Through a visual assessment of the calculated slopes, it was noticed that the slopes of bridges and tunnels tended to be incorrect due to the elevation difference between segments on bridges or in tunnels and the terrain (captured by the DEM). Very short segments lying on the boundary of two DEM raster cells further could have unrealistically high slopes. These effects should be corrected in the next step.

The elevation of points belonging to bridges was supplemented using the swissSURFACE3D dataset. The dataset contains LiDAR data points capturing the elevation of the surface, including the built environment. Since it contains, on average, 15-20 data points per square meter, the number of points was first sampled down to one third and then filtered to elevation points from bridges. It was noticed that edges at the end of bridges often have one node on the bridge with an elevation difference between the bridge and the terrain. For the other node that is often off the bridge, the elevation of the street and the terrain is the same. Such segments towards the end of bridges are often not tagged as such in OSM, although they belong to bridges and therefore have an incorrect modeled slope using the DEM. Edges having a direct connection to an edge tagged as a bridge were therefore also included in the subset with bridges. The elevation of the nodes in the subset with bridges was determined using the nearest bridge LiDAR point, if it was less than 30 meters away. A threshold distance of 30 meters was found to be a good compromise to still get an elevation for points at the border of bridges, but to not assign a wrong elevation. If for one node of a segment the nearest LiDAR data point was more than 30 meters away, the elevation calculated based on the DEM was used. If bridges got a slope greater than 12% using the LiDAR points, the slope using the DEM was used. The swissSURFACE3D dataset did not cover the city of Bern by December 2023. Originally, it was planned that the dataset achieves full coverage for Switzerland by 2023 (swisstopo, 2023d). The slopes of bridges in the city of Bern were therefore manually adjusted. For all cities, the slope of tunnels was set to 0%. The slopes in the networks were again visually checked, especially around bridges and tunnels. Some single cases were corrected by hand (using Google Earth or city maps). To deal with incorrect slopes for short segments, it was decided to set the slopes of segments with an absolute average slope larger than 30% and a length below 20 meters to not known (NA).

The slope multipliers to later calculate perceived distances were defined similarly as in Grigore et al. (2019), and Wysling and Purves (2022). Since an undirected network was used, in which the direction of travel does not matter, the absolute average slope was used to assign cost factors. As indicated in Table 5, the cost factors (c_s) were defined based on four slope categories. In their route choice model of cyclists in Portland, USA, Broach et al. (2012) find that this specification performs best. Network segments with a slope between 0-2% received a slope multiplier of 0. If just the slope is considered, the perceived distance is equal to the actual distance for segments with such a multiplier. Segments with a slope of NA were also assigned to the slope category of 0-2%. The highest slope multiplier of 1.5 was used for segments with a slope of 6+%. The multiplier indicates that cyclists are willing to add 150% to their travel distance to avoid a slope of 6+%. In terms of perceived distance, it means that a segment with a slope of 6+% receives a perceived distance 150% longer compared to its actual length because of the slope. The multipliers for the three lowest slope categories are the same as in Wysling and Purves (2022). They are therefore also lower in comparison to the study by Broach et al. (2012) to not overestimate the effect of slopes in the overall cycling quality modeling. With the same intention, the multiplier of the highest category was set to 1.5.

Table 5 Cost factors for different slope categories.

Slope category	Slope multiplier (c_s)
0-2%	0.0
2-4%	0.4
4-6%	1.0
6+%	1.5

4.3.3 Green and aquatic areas

The positive influence of green and aquatic areas on cycling quality was modeled through the share of such areas surrounding network segments. This modeling step was identified as the main bottleneck in the workflow concerning processing times. Therefore, an external server using an SSH (Secure Shell) instance was used for this calculation. To calculate the share, the three datasets with green areas, aquatic areas and trees had first to be merged into one. The trees were provided as a point dataset. To later calculate areas, it was necessary to convert the trees dataset into a polygon dataset. The points were converted to circles using a buffer with a radius of 4 meters around the points. The buffer size of 4 meters was set, because the mean value and the default value of the width for trees in the city of Zurich is 8 (2x4) meters (Stadt Zürich, 2023a). To only include trees affecting cycling quality, they were filtered to center points which lie inside the network buffered with a size of 10 meters (on each side of the segments). This threshold seems reasonable to consider trees along segments in the network and to exclude, for example, trees behind buildings. After the trees were merged with the OSM data, the network segments were buffered with a size of 10 meters on each side to calculate for each segment the share of the buffer covered by green and aquatic area. The final values therefore lie between 0 (0%) and 1 (100%). A segment with a value of 0.75, for example, indicates that 75% of its buffered area is covered by green and aquatic areas.

Given that the coverage of green and aquatic areas positively affects the cycling experience, its factor was treated as a benefit instead of a cost multiplier. In comparison to the two other cycling quality factors slope and BLOS, the multiplier for green and aquatic areas was defined using a continuous function and not given discrete values:

Equation 1 Benefit function defining benefit multiplier (b_{ga}) using the share of green and aquatic area surrounding a segment (s_{ga}).

$$b_{ga} = 0.1 - \frac{0.1}{0.01 + e^{0.05 * s_{ga}}}$$

The used benefit function provided in Equation 1 assigned a benefit multiplier (b_{ga}) to each network segment depending on the share (in percentages) of the buffered segment that is covered by green and aquatic areas (s_{ga}). The benefit function was defined as by Grigore et al. (2019). For pedestrians, the presence of greenery reduces the perceived travel time by 20% compared to the actual travel time (Erath et al., 2017). Because it can be assumed that for bike trips with a utilitarian purpose directness is more important, the function was defined such that the maximum benefit multiplier is 10%. The function further has the characteristic that coverages of 30-40% achieve a relatively high benefit factor. Coverage values under 10% lead to a low benefit multiplier. Figure 11 shows the graph corresponding to the used benefit function.

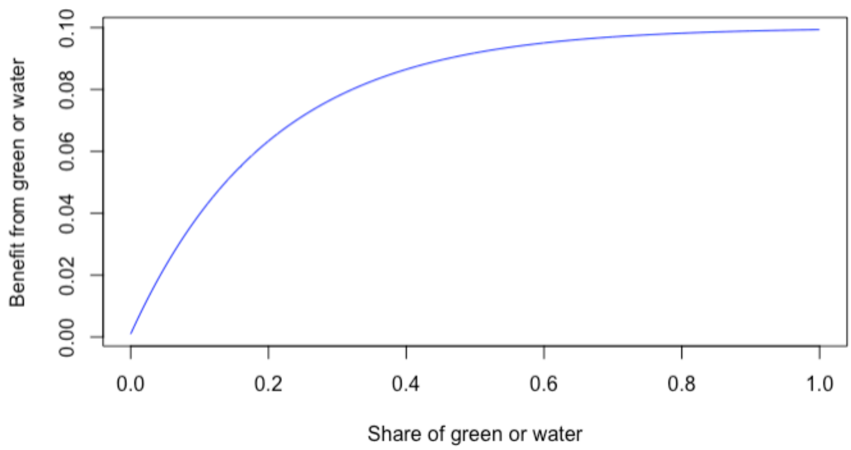


Figure 11 Function defining the benefit factor given the share of green and aquatic areas surrounding a network segment.

4.3.4 Perceived distance

As shown in Equation 2, the two cost multipliers and the benefit multiplier were used to scale the actual distance in meters for all segments in the network to get the perceived distance ($d_{per,s}$):

Equation 2 Scaling of the actual segment length using the three previously defined multipliers.

$$d_{per,s} = (c_{BLOS,s} + c_{s,s} - b_{ga,s}) * d_{act,s}$$

where $d_{act,s}$ is the actual segment length [m], $c_{BLOS,s}$ the BLOS multiplier, $c_{s,s}$ the slope multiplier and $b_{ga,s}$ the benefit multiplier for green and aquatic areas of network segment s. Considering all three multipliers together, the lowest possible multiplier is 0.7 and the highest possible multiplier is 3.3. A total multiplier below 1.0 means that the perceived distance is shorter than the actual distance, indicating a high cycling quality. With multipliers above 1.0, the perceived distance is longer than the actual distance. In the next step, the resulting perceived distances for each segment were used for the shortest route calculation in the gravity-based bikeability index approach.

4.4 Bikeability

Traffic coverage qualities not only capture the mere spatial accessibility, but further qualitative aspects. The Swiss public transport quality classes, for example, consider the distance to public transport stations together with their service level. Similarly, bikeability as defined in this thesis (compare Section 2.4), combines spatial accessibility to important destinations with aspects such as perceived safety and comfort (Lowry et al., 2012). This makes bikeability indices a suitable measure of the traffic coverage quality by bike. To assess bikeability in the four case study areas, a gravity-based bikeability index was applied. Using perceived network distances, gravity-based approaches facilitate the integration of cycling quality into spatial accessibility assessments. The perceived network distances are calculated based on the shortest routes between origins and destinations.

4.4.1 Origins and destinations

The bikeability index was calculated per populated hectare raster cell (100 x 100 m) for all four municipalities, using the STATPOP dataset (BFS, 2023a). As noted by the Federal Department of the Environment, Transportation, Energy and Communications, this should be the priority level of analysis to measure traffic coverage qualities in Switzerland (UVEK, 2015). It directly captures the traffic coverage quality of the residential population. The traffic coverage quality can further be aggregated to higher levels, e.g., to traffic zones. Furthermore, the Swiss national law on cycle paths presented in Section 3.1.1 focuses on residential locations. For the routing calculations, the hectare raster cell centroids were used. They were the origins of the calculated routes. Each centroid of a populated hectare raster cell will receive a bikeability index value.

Since the bikeability index should capture the general traffic coverage quality by bike, it does not focus on one destination type. Multiple types of destinations were included instead. According to the Swiss national law on cycle paths, network segments should connect particularly locations of residence, working places, schools, public transport stations, public facilities, grocery stores, leisure and sports facilities and cycle paths for recreational purposes. In Section 2.2, the importance of reachable public facilities and destinations to satisfy daily needs for the inclusiveness and sustainability of cities has been underlined. Therefore, the following types of destinations were included in the analysis: Train stations, schools, leisure and sports facilities (leisure facilities, public swimming pools, public sports facilities, zoos), hospitals, public parks and grocery stores. These types of destinations are further mentioned to be important in the Swiss bicycle manual (Capirone et al., 2008). Working places were not explicitly included, as the average commute in Switzerland is 13.6 km long and can therefore be considered too far to be covered by bike for most people (BFS, 2023b). 71% of all commuters do not work and live in the same municipality (BFS, 2023b). If working places had been included, they would have heavily influenced the accessibility calculation, even though most people do not work within biking distance of the location of residence. Moreover, spatial accessibility to non-work destinations also influences travel behavior and quality of life (Iacono et al., 2010). However, trips to work are indirectly covered through the included train stations for multimodal trips to work. Since most types of destinations are public facilities and the bike networks should connect to destinations within a municipality (Kanton Zürich, 2021), the destinations were filtered to the municipality boundaries, as the population data (origins). To have all destinations as Points of Interest (POIs) for the routing calculations, destinations provided as areas were replaced by their centroid.

One hospital could consist of multiple grounds in the data. To not overestimate the number of hospitals at a location, the grounds were merged by the name of the hospital and the centroid of the merged grounds was used as the POI. It has further been noticed that some minor privately owned clinics are included in the dataset. Since the analysis should focus on the major public hospitals in the municipalities, only hospitals with grounds above a certain threshold area were included. The threshold was assessed visually for each city separately, but is roughly at 4'000 m^2 for all cities. Similarly, a threshold area of 2'000 m^2 was set for parks. The schools were filtered to the secondary level of education. Primary schools and universities were excluded from the analysis. The analysis was restricted to schools providing secondary level of education, because they are less densely and homogenously distributed compared to primary schools. Universities were neglected to not overestimate bikeability to tertiary education. A university consists of multiple buildings and areas distributed in a city.

The raw points of interest were used for the bikeability calculation. The POIs were not aggregated, i.e., counted on a regular grid. An aggregation of the points to a regular grid of 200 x 200 m showed that most of the grid cells either contain no or just one destination.

4.4.2 Routing

For the calculation of the routes on the network between origins and destinations, the points were assigned to the nearest node in the network. A potential bias in this calculation of the routes could have been their distance into the bike network, i.e., to the nearest node in the network. If the distance to the nearest network node is long for a given population point, the calculated route lengths would systematically underestimate route lengths. The histograms of the distance to the nearest network node for the population and destination points of all four cities in Figure 12 and Figure 13, however, show that distances into the network are short. The bike networks consist of short network segments, implying a high node density. To check if routes can be calculated, exemplary shortest paths were calculated on each of the four networks. Using the network for the city of Zurich as an example dataset, the quality of the shortest paths has further been assessed. The shortest path between some random origins and destinations was compared to the shortest path on Zurich's routing engine (Stadt Zürich, 2023b). The comparison was conducted using the real distances along the network and the perceived distances. It was not the ambition to produce completely accurate routes with the simple routing algorithm. Nevertheless, the comparison revealed that the modeled routes roughly correspond to the ones in the routing engine. Particularly, the simple routing algorithm with the perceived distances is able to detect the included aspects of cycling quality, like the topography and the type of bike infrastructure.

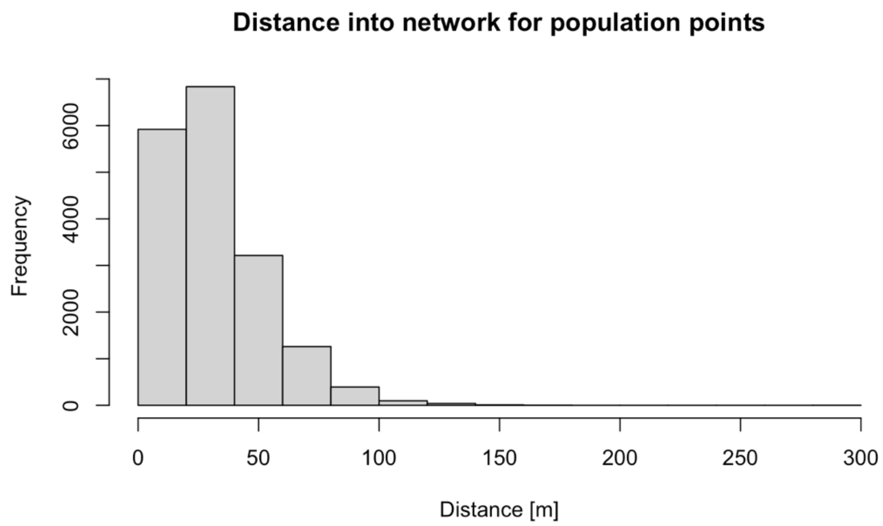


Figure 12 Histogram with distances to the nearest network node for the population points.

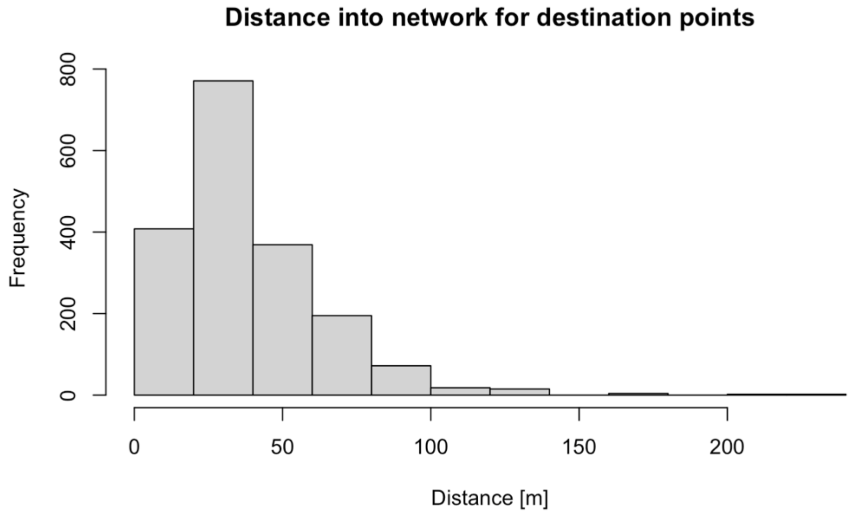


Figure 13 Histogram with distances to the nearest network node for the destination points.

To calculate the routes from origins to destinations, the st_network_cost function from the R package sfnetworks was used. It calculates the shortest path between two points using Dijkstra's shortest path algorithm (Dijkstra, 1959). With this function the shortest path using the actual distances of the edges was calculated for every population point to all destination points in the municipality. For the further analysis, only destinations to which the shortest actual distance is 4 kilometers or lower were considered for each population point. Destinations farther away were excluded in the bikeability index calculation, as they are assumed to be inaccessible by bike. The threshold travel distance of 4 kilometers was set based on the distribution of bike trip lengths in Switzerland. Roughly 80% of all bike trips in Switzerland have a length of 4 kilometers or lower (BFS and ARE, 2023). For the destinations within the threshold travel distance of 4 kilometers, the perceived shortest distance was additionally calculated.

4.4.3 Calculation bikeability index

The perceived shortest distances were used to calculate the bikeability index. For the calculation of the index a gravity-based approach, as introduced in Section 2.4.2, was used. First, bikeability $b_{i,t}$ was calculated for every population point i for each destination type t separately, using the following equation:

Equation 3 Formula to calculate the destination type specific bikeability index value for all population points.

$$b_{i,t} = \frac{\sum_{j \in t}(d_j * e^{-\beta * p_{ij}})}{\sum_{j \in t} d_j}$$

where p_{ij} is the perceived shortest distance [m] to destination *j* of type *t* within the threshold distance of 4 km and d_j is the weight (attractiveness) of destination *j*. Only for train stations weights were introduced based on attractiveness/importance. In the calculation for the bikeability to train stations, the weighted average was taken, where the weight d_j corresponds to the category of the station. Each train station in the data is associated with a station category from high (=1) to low (=5) level of service. To capture the attractiveness of train stations, the scale for the categories was inverted. The more important a train station, the higher its weight d_j. For all other destination types, the average value of all reachable destinations was taken, which equals to d_j=1.

The negative exponential impedance function in Equation 3 discounts destinations with increasing perceived distance or travel impedance. Destinations farther away receive a lower value than destinations closer to the population point. In the literature, different mathematical functions have been used as travel impedance functions (Grengs, 2015). The most common type of function to capture the distance-decay effect in transportation planning models is the negative exponential function (Meyer and Miller, 2001). In comparison to power functions, negative exponential functions decline more gradually. Consequently, they are better suited for non-motorized transport like cycling (Iacono et al., 2010). The parameter β captures peoples' unwillingness to travel long distances. The larger the value of β, the more rapidly the willingness to cycle decreases with increasing travel distance. Similar to Hamidi et al. (2019) and UVEK (2015), the parameter β for this project was chosen based on the travel survey among the Swiss population. It was set to the value, for which the negative exponential impedance function reaches 0.2 (20%) at the set travel distance threshold of 4 kilometers. As noted above, roughly 20% of the bike trips in Switzerland are longer than 4 kilometers, 80% are shorter or equal to the threshold value (BFS and ARE, 2023). Because of the gravity-based approach with a negative exponential impedance function, the values of the bikeability index lie between 0 and 1 for each destination type.

The last step of the calculation was to aggregate the destination type specific bikeability index values to an index value capturing the general traffic coverage quality. For the aggregation to one single value, the approach of integrated spatial accessibility, as described by Ashik et al. (2020) and Li et al. (2021), was applied. For each population point *i*, the weighted average of the destination type specific values was taken as follows:

Equation 4 Calculation of the total bikeability index as a weighted average of the destination type specific bikeability values.

$$b_{i,tot} = \sum_{t \in T} w_t * b_{i,t}$$

where $b_{i,tot}$ is the total bikeability index value of population point i, w_t the relative weight of destination type t and $b_{i,t}$ the destination type specific bikeability index value. Like the β parameter in the impedance function, the weights for the different destination types were determined based on the Swiss travel survey as good as possible (BFS and ARE, 2023). The relative weights are illustrated in Table 6. The relative frequency of daily trips to destinations of a certain type were used as relative weights. The provided number of trips with a purpose leisure time was equally distributed to the two destination types public parks and leisure and sports facilities. For hospitals, no trip frequency was provided in the micro census. Since it can be supposed that hospitals are less frequently visited compared to the other destination types, a number of trips per day of 0.05 was assumed. The average number of trips per day to train stations was set to 0.2. This number for train stations coincides with the average number of times a Swiss person travels by train per day (BAV, 2023a). The weights (w_t) were determined based on the relative trip frequency of the included destination types. Therefore, the relative weights sum up to 1.

Table 6 Average number of trips per day and purpose (BFS and ARE, 2023). The values for train stations and hospitals had to be assumed.

<table>
<tr><th></th><th>Number of trips per day</th><th>Relative weight (w_t)</th></tr>
<tr><td>Shopping</td><td>0.7</td><td>0.33</td></tr>
<tr><td>Schools</td><td>0.2</td><td>0.09</td></tr>
<tr><td>Leisure and sports facilities</td><td rowspan="2">1.0</td><td>0.23</td></tr>
<tr><td>Public parks</td><td>0.23</td></tr>
<tr><td>Train stations</td><td>0.2</td><td>0.09</td></tr>
<tr><td>Hospitals</td><td>0.05</td><td>0.02</td></tr>
</table>

As the destination type specific bikeability index values, the total bikeability index values also lie between 0 and 1. The higher the index value, the higher the bikeability for a given population point. Bikeability was illustrated on maps for each of the four cities. Maps were produced for the total bikeability index, but also for each destination type separately. The values of the bikeability index were mapped on a scale from low bikeability to high bikeability using the deciles of the index distribution over all four case study areas.

4.4.4 Sensitivity analysis: Number of accidents

As illustrated in Chapter 2, it is rather the subjective safety that influences the behavior of cyclists and not the objective safety. The three factors included to model cycling quality (BLOS, slope, and green and aquatic areas) capture the perceived safety and comfort for cyclists. However, a sensitivity analysis was conducted additionally accounting for the objective safety by including locations of reported bike accidents. The inclusion of bike accidents should allow to see if and how the results of the bikeability analysis change.

The point dataset with reported bike accidents in Switzerland was filtered to the four most recent years available in the data (2019-2022) and to accidents that are at most 10 meters away from a bike network segment. The bike accidents were then assigned to the nearest network edge and the number of accidents was determined for each segment. Since data on the amount of bike traffic was not available for the bike networks, exposure could not be accounted for. The absolute number of bike accidents per edge was used for the analysis and not, for example, the relative frequency accounting for the number of cyclists on a segment. For the sensitivity analysis with bike accidents, the workflow to calculate bikeability as described in this chapter was repeated, except that an additional cost factor for bike accidents was introduced for the calculation of the cost distances. Equation 2 can therefore be rewritten as follows:

Equation 5 Cost distances, expanded by the cost factor for the number of accidents.

$$d_{cost,s} = (c_{BLOS,s} + c_{s,s} + c_{a,s} - b_{ga,s}) * d_{act,s}$$

where $c_{a,s}$ is the additional cost factor for the number of accidents. The cost factor was set to 0 for segments without any reported bike accident. Segments with one reported bike accident received a cost multiplier of 0.2 and segments with more than one accident a cost multiplier of 0.6. Therefore, the lowest possible total multiplier to calculate the cost distances remained at 0.7, as with Equation 2. The highest possible total multiplier increased from 3.3 to 3.9.

4.5 Isolate effect of bicycle infrastructure on bikeability

The implemented bikeability index was calculated based on perceived distances between the origins and destinations. It therefore captures the cycling quality on the routes to destinations. Nevertheless, the index values are heavily influenced by the actual distance to destinations. A population point with many destinations very close to it, automatically has high bikeability values, although the cycling quality of the streets to these very close destinations might be bad. Particularly, for policymakers it is interesting to isolate the effect of bike infrastructure. Such an isolation allows to see from which locations suitable bike infrastructures leading to important destinations are already present. Similarly, it shows from which locations of residence people are relatively deprived of suitable bike infrastructure to reach important destinations. Together with the assessed bicycle level of service of network segments, it could be assessed where further improvements of bike infrastructure are needed.

To isolate the effect of bike infrastructure, the mean distance to destinations within the threshold travel distance of 4 km was calculated based on two different distance measures for each population point. Once, the mean distance to reachable destinations was calculated using the actual distances, and once with perceived distances just considering bike infrastructure. To get the perceived distances based on bike infrastructure, just the BLOS multiplier was used to scale the actual distances. Hence, Equation 2 can be rewritten as follows:

Equation 6 Scaling of the actual segment length just considering BLOS.

$$d_{per,s} = c_{BLOS,s} * d_{act,s}$$

The percentage change in mean distance using the perceived distance considering BLOS compared to the actual mean distance was used as a measure of bike infrastructure quality for trips from a given population point. A large percentage number indicates that the mean distance to reachable destinations is considerably higher when bike infrastructure is considered, compared to the actual distances. This indicates that the bike infrastructure quality is relatively low for trips originating at such a population point. The relative change in mean distance was preferred to the raw change in mean distance, such that an increase of 100 meters from a base of 800 meters, for example, can be treated differently to an increase of 100 meters from a base of 2000 meters.

5 Results

The final and intermediate results of the analysis are outlined in this chapter. Section 5.1 summarizes the characteristics of the bike networks and the POIs used for the bikeability calculation. In Section 5.2, the intermediate results of the bicycle suitability modeling are presented. The results of the bikeability index analysis are shown in Section 5.3 (RQ1). Section 5.4 presents the effect of bike infrastructure on bikeability and shows where people are relatively deprived of suitable bike infrastructure to reach important destinations (RQ2). For the geographical context and the micro toponyms in the discussion of the results, please refer to Figures 7-10 in Chapter 3.

5.1 Bike networks and destinations

Overall, the bike networks consist of short network segments (see Table 7). The shortest segment is less than one meter long for all four cities. The median segment length is the longest in Winterthur (46.0 meters) and the shortest in Zurich (28.6 meters). There are some segments with a length of a few hundred meters in each city. However, these are outliers and most of the segments have a length below 100 meters. Lausanne has the network with the highest total length. But it is important to note that for Lausanne the network data were clipped to the bounding box of the municipality and not the borders of the municipality as with the other three cities. The reason to use a different extent for Lausanne was to avoid that the networks in the two parts of the municipality are disconnected (compare Section 3.1.3 and Section 4.2).

Table 7 Distribution of segment lengths and total network lengths.

	Shortest [m]	Median [m]	Longest [m]	Total network length [m]
Bern	0.2	33.6	467.2	831’289
Lausanne	0.6	38.1	636.2	1’583’869
Winterthur	0.6	46.0	452.8	988’222
Zurich	0.4	28.6	399.3	1’537’572

Figure 14 shows the points of interest that act as destinations in the gravity-based bikeability calculation for each of the four municipalities. As described in Section 4.4.1, the following destination types were considered: Grocery stores, leisure and sports facilities, schools, hospitals, public parks and train stations. Grocery stores and schools are evenly distributed in all four case study areas. Train stations, in contrast, are less evenly distributed. Whereas leisure and sports facilities are also present in the city centers of Bern, Winterthur and Zurich, they are more concentrated towards the municipality borders in Lausanne.

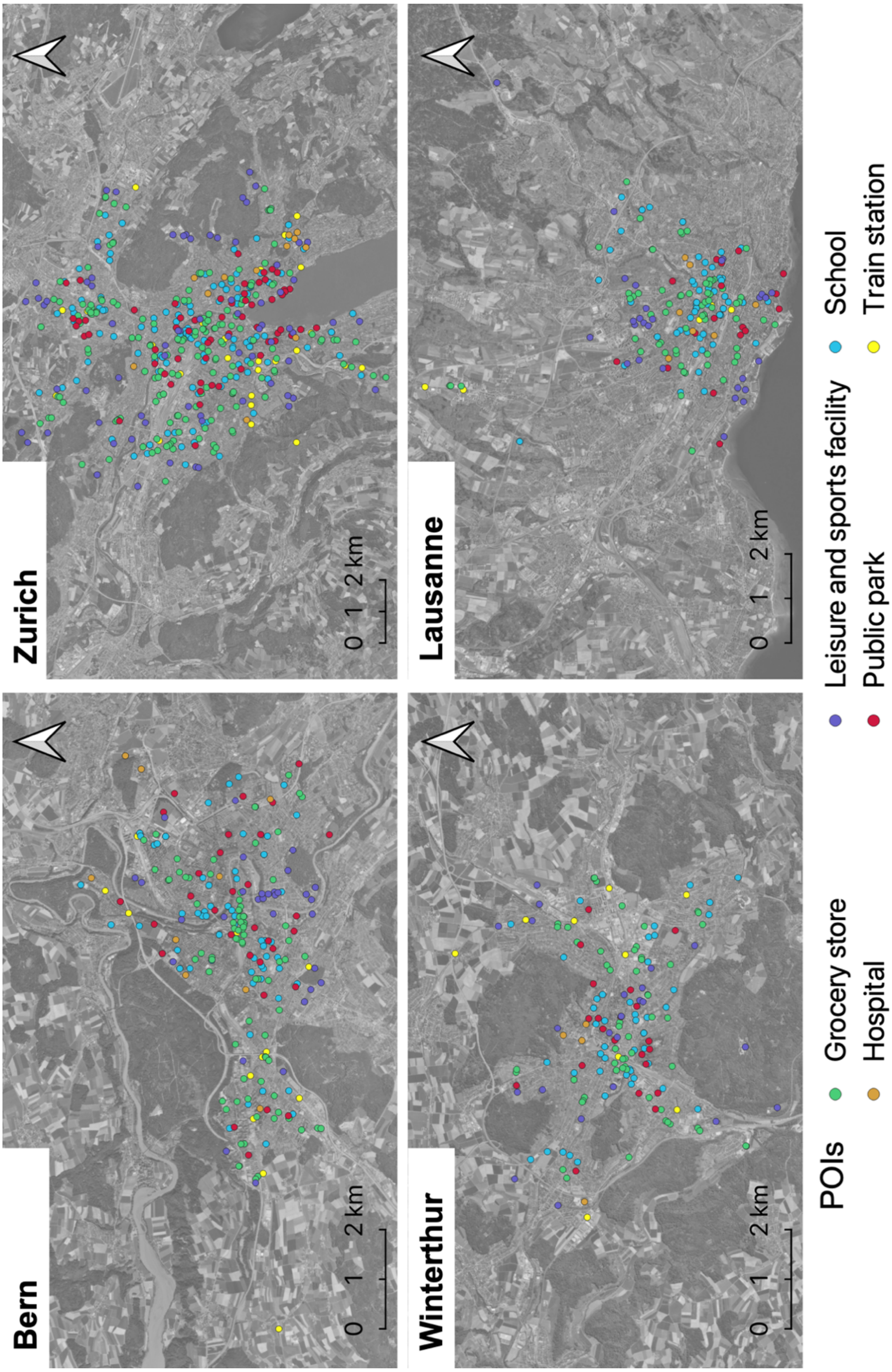


Figure 14 POIs used for the bikeability calculation.

5.2 Bicycle suitability

5.2.1 BLOS

To model bicycle level of service (BLOS), the type of bike infrastructure and the speed limit were combined to score each network segment from A (most suitable for cycling) to F (least suitable for cycling). Figure 15 presents the share of total network length belonging to the different BLOS categories for the four case study areas. Segments with a score of A or B either provide an infrastructure physically separating cyclists from motorized traffic (cycleway or footway) or have a speed limit of 30 km/h or lower. They can therefore be considered as suitable for cycling. The largest share belongs to service level B. The large share of this BLOS category is attributable to the fact that footways and streets with a speed limit of 30 km/h belong to this same service level. Particularly, network segments with an OSM *highway=service* tag belong to this category. These mainly short segments provide the final connection to buildings. However, over the whole network they sum up to a considerable share. Network segments with a BLOS of E or F have a speed limit of 50 km/h without any bike infrastructure or of above 50 km/h without an infrastructure physically separating cyclists from motorized traffic. The high speed limit and the low degree of separation from motorized traffic make these segments least suitable to cycle on. Bern has the highest share of BLOS A and the lowest share of BLOS F. In Lausanne, the share of BLOS A is the lowest, and the share of BLOS F the highest.

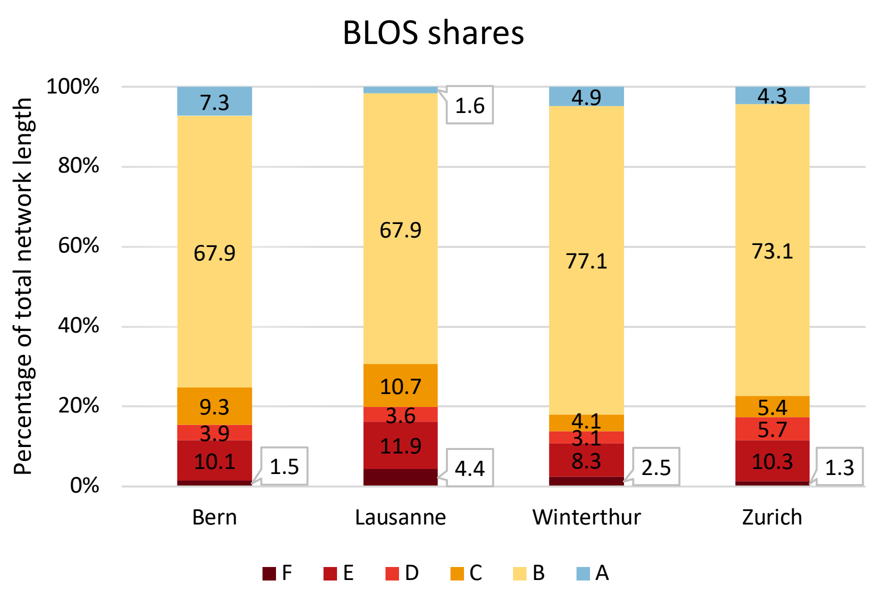


Figure 15 Share of total network length belonging to the BLOS scores A-F for each case study area.

Figure 18 illustrates the bike networks for the four case study areas, with the network segments colored depending on their modeled BLOS. Some sections of the major road axes have a comparably high BLOS of B or C. But in all cities, the main road axes without a speed limit reduced to 30 km/h or below can be recognized in red with a relatively low BLOS score.

5.2.2 Slope

Figure 19 depicts the slope of all network segments in percentages, using the four categories of absolute average slope: 0-2%, 2-4%, 4-6% and 6+%. In the three cities located in the Swiss German speaking part, the steepest slopes are concentrated towards the hills in the municipalities. In Bern, some steep segments are distributed around the river Aare, for example, in Altenberg. But the steepest slopes mainly lead through less densely populated areas such as Chünizbergwald in the south, Eymatt in the north and Oberbottigen in the west. The steepest slopes in Zurich can be identified towards the Uetliberg in the southwest and the Zürichberg and Witikon in the east/southeast. Steep slopes are further located in Höngg and Unterstrass. Similarly, the steepest slopes in Winterthur are present on the hills distributed around the city center (e.g., Eschenberg, Lindberg and Neuburg). Opposed to the other cities, network segments belonging to the highest slope category are more evenly distributed in Lausanne. Slopes are not only steep towards the outskirts, but also in the center. In general, there are more steep network segments than in the other municipalities. The reason for this is that the whole municipality is located on a hill on the northern shore of Lake Geneva. One can see that streets and footways running along the lakeshore belong to the lowest gradient category.

The relative frequency of the four slope categories is shown in Figure 16. The figure summarizes the share of the total network length belonging to the four slope categories. In line with the visual assessment, Lausanne's bike network has the highest share of the highest slope category (25.2%). The share is more than twice as high as for the city of Bern (11.2%). Opposed to Lausanne with 34.7%, more than 50% of the total network length has an average slope of 0-2% for the other three cities.

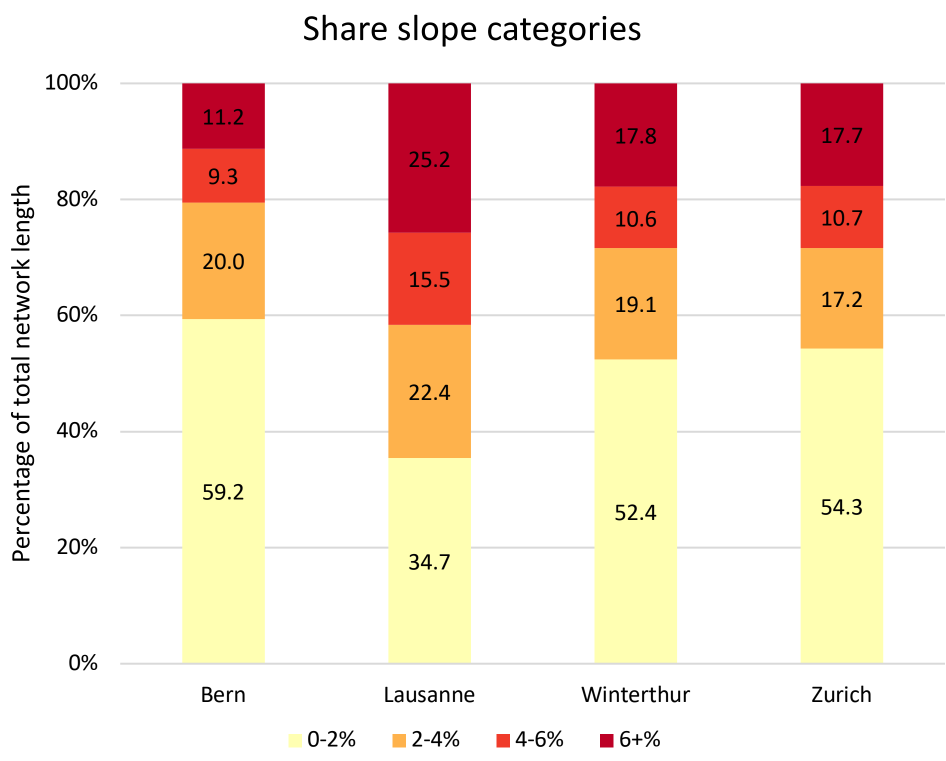


Figure 16 Share of total network length belonging to the different slope categories.

5.2.3 Green and aquatic areas

The third factor considered to model cycling quality was the natural environment of the network segments. Large waterbodies, green areas and trees were included in the analysis. Figure 20 shows the share of the segments buffered with 10 meters (on each side) covered by green and aquatic areas. Of course, the segments with the highest coverage are in the forests on the outskirts of the cities. In Bern, Winterthur and Lausanne, the segments with the highest shares tend to be in areas with steep slopes. The largest clusters with high shares in Bern are in Bremgartenwald and Chünizbergwald. In Winterthur, the segments with the highest values are on the wooded hills (e.g., Lindberg, Eschenberg and Hegiberg). Zürichberg, Käferberg and Hönggerberg are areas in the city of Zurich with a concentration of high shares. The correlation between the share of green and aquatic areas and the slope is less apparent in Lausanne compared to the other three cities. The area between Montheron and Vers-chez-les-Blancs is the largest cluster of high shares in Lausanne. In all four cities, lower values are concentrated in the more densely built city centers. Nevertheless, since trees and parks were included in the analysis, also streets in the city center can have a share of green and aquatic areas above 0%.

Figure 17 summarizes the distribution of the share of green and aquatic areas for the network segments with a violin plot for all four case study areas. The minimum share is 0% and the maximum is 100% in all four cities. The median (in red) and the mean (in blue) share value is the highest in Winterthur, whereas they are very similar for Bern, Lausanne and Zurich. While the density of values near 0% is lower, the density of values near 100% is higher for Winterthur in comparison to the other three cities. The wooded hills in Winterthur cover a larger share of the municipality area compared to the other three case study areas. The width at the bottom of the violin plot is the longest for Zurich, indicating that Zurich has a particularly high density of values of or near 0% compared to Bern, Lausanne and Winterthur.

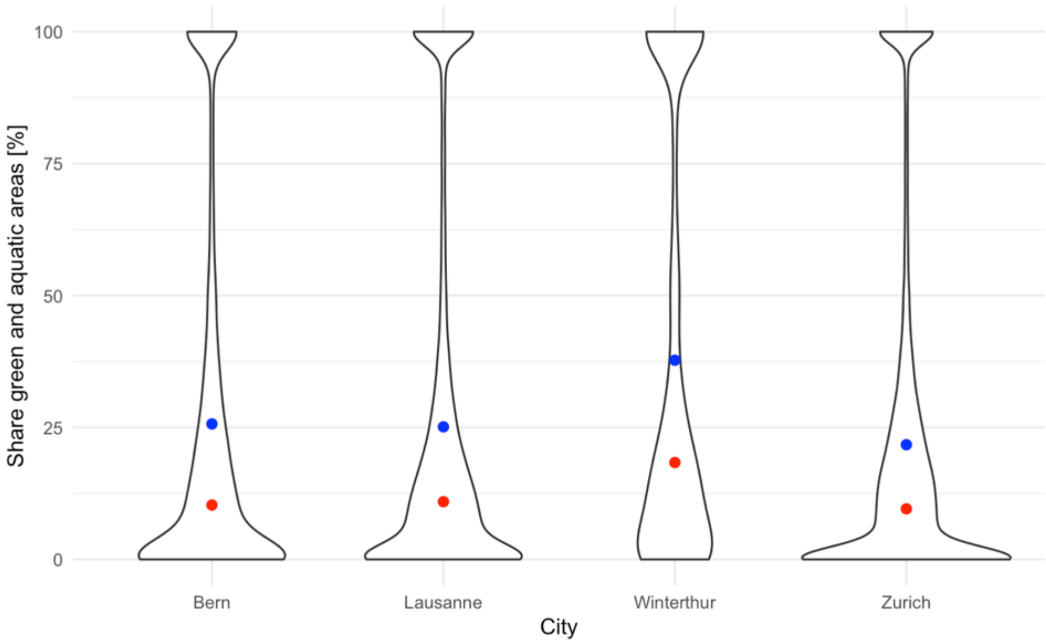


Figure 17 Violin plots of the share of green and aquatic areas with the median (red dot) and the mean (blue dot).

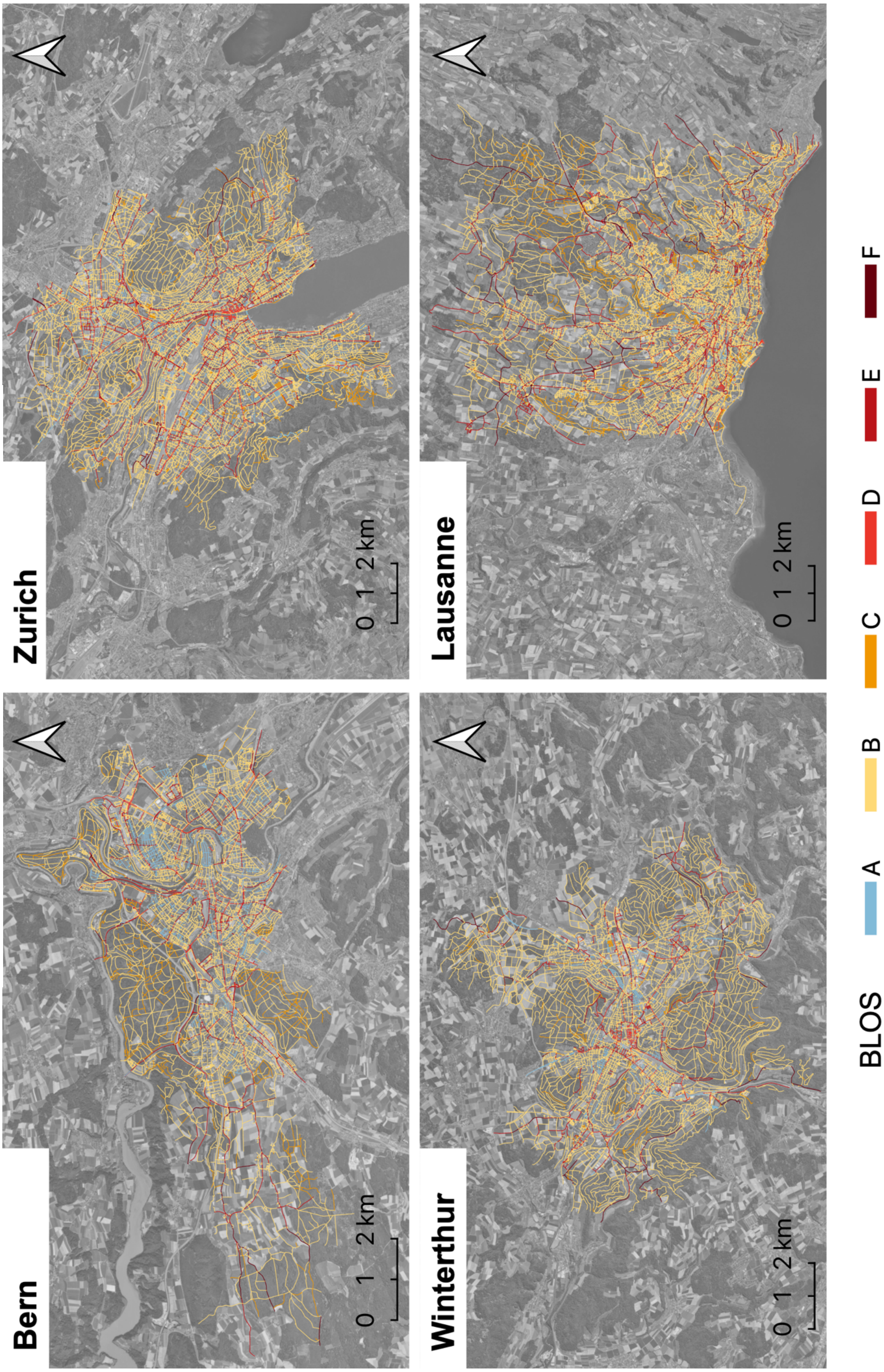


Figure 18 BLOS scores of the segments in the bike networks.

Figure 19 Category of absolute average slope of network segments.

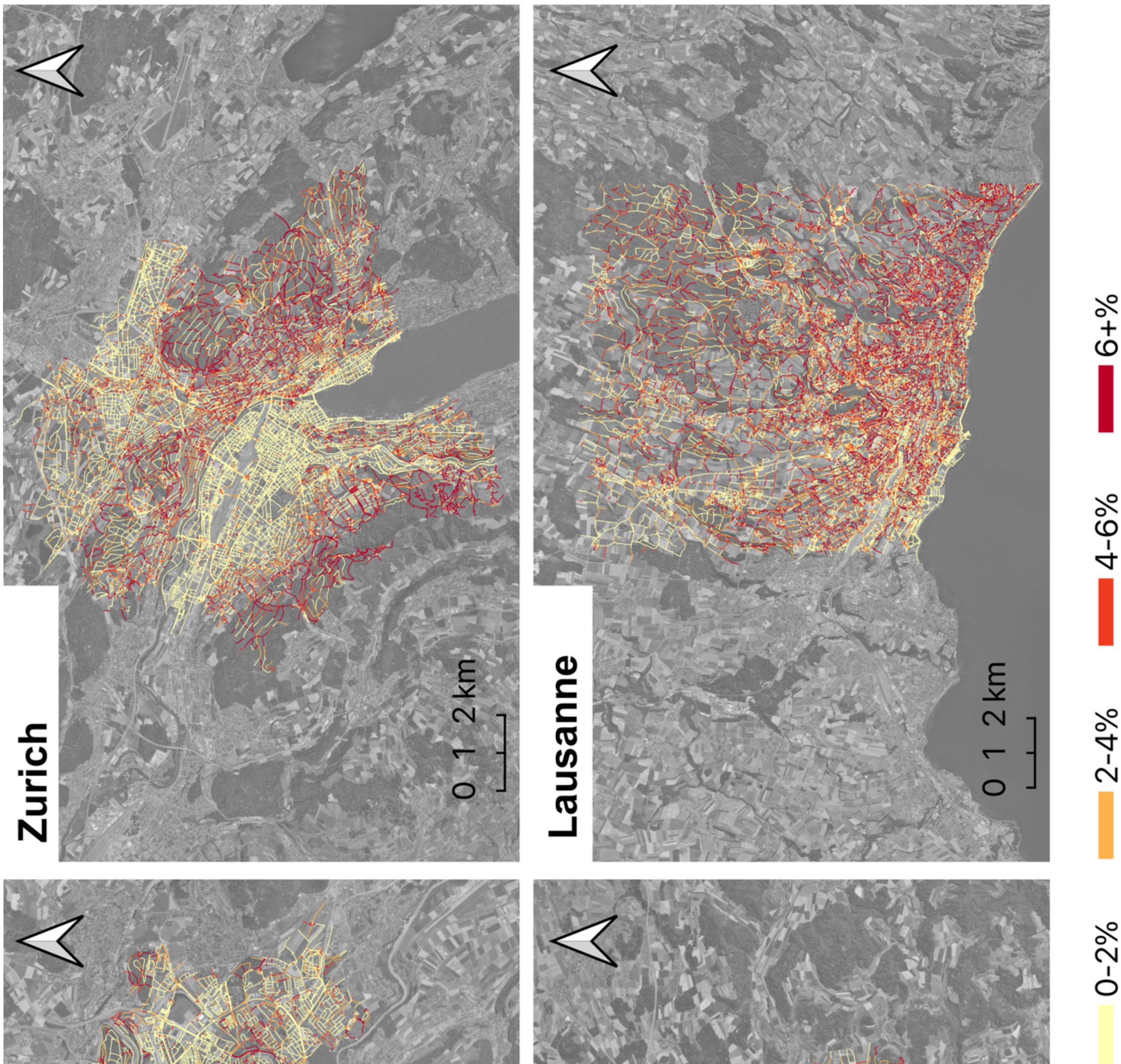
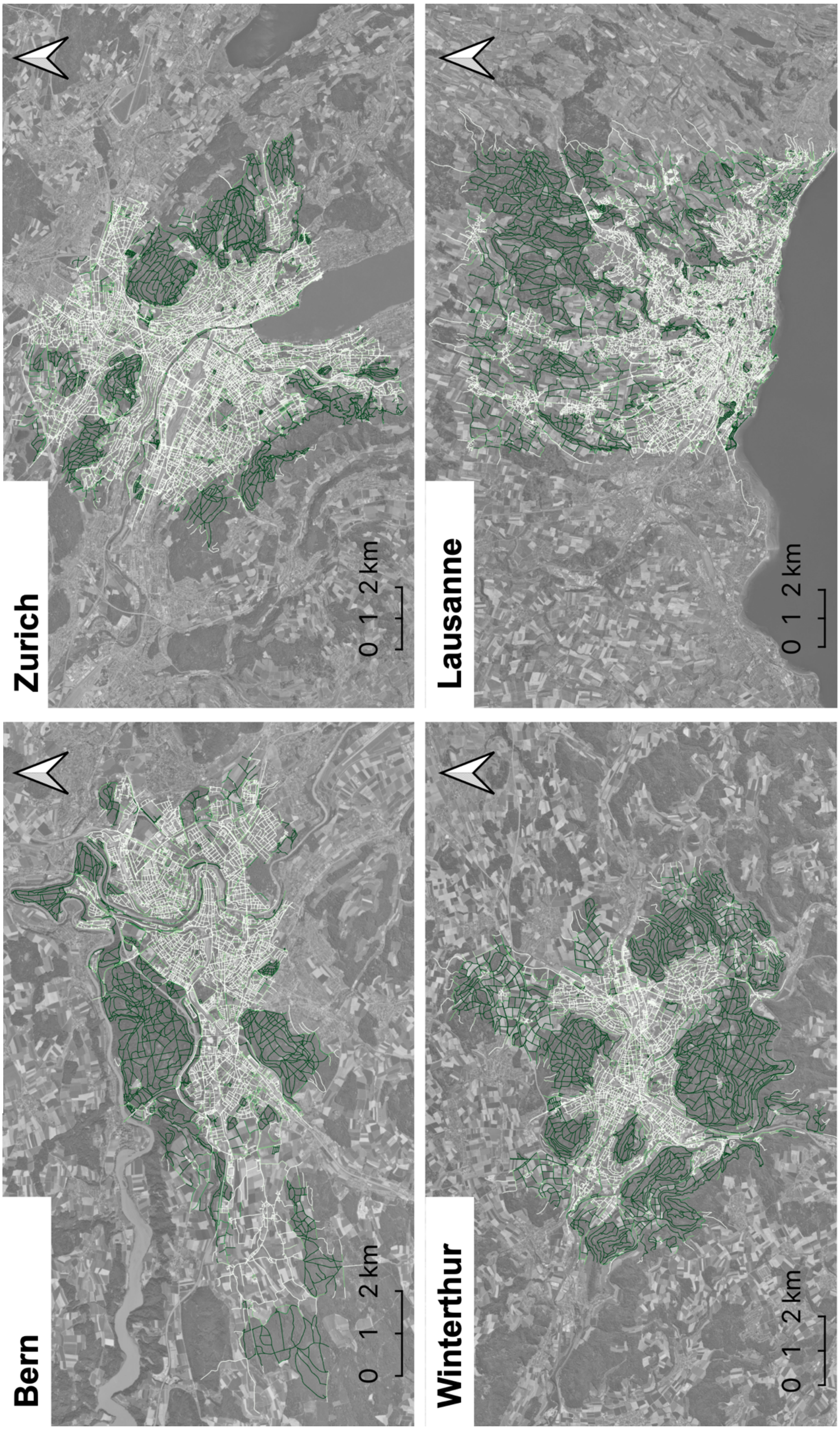


Figure 20 Coverage of green and aquatic areas surrounding network segments.



5.3 Bikeability

The assessed bicycle suitability was used to calculate perceived distances for the gravity-based bikeability index. Bikeability was first calculated for each destination type separately before the total bikeability index to capture the general traffic coverage quality by bike was calculated. Because of the gravity-based approach described in Section 4.4.3, the values of the index lie between 0 and 1. The higher the index value, the higher the bikeability. The produced bikeability maps show the deciles of the bikeability index based on the populated hectare raster cells of all four cities together. This quantile classification allows to investigate within- and between-city variation simultaneously. The lowest decile includes the lowest 10% of the bikeability index value distribution over all four cities (low bikeability) and the 10^{th} decile the 10% of the populated hectares with the highest value (high bikeability). Destination type specific bikeability to train stations is shown in Figure 21. The maps for the other types of destinations (leisure and sports facilities, public parks, schools, hospitals and grocery stores) are in Appendix C.

As a result of the chosen gravity-based bikeability approach, the highest bikeability index values for train stations can be found in areas with train stations nearby. In Lausanne, the highest values are strongly concentrated around the main station in the city center. In contrast, the highest values in Bern and Zurich are not concentrated around the main stations in the city center, but around train stations on the outskirts. Other train stations farther away within the maximum travel distance of 4 km drag down the bikeability values around the main train stations in these two cities. In Zurich, bikeability to train stations is modeled higher in Oerlikon, for example, than in the city center around the main train station. The highest bikeability values for train stations in Bern are concentrated in Bümpliz and Bethlehem with a high density of train stations and not around the main station in the city center. In Winterthur, values from the 10^{th} decile can be found in the Altstadt, but they are further distributed towards the borders in Talacker and Guggenbühl in the northeast, where additional train stations are located.

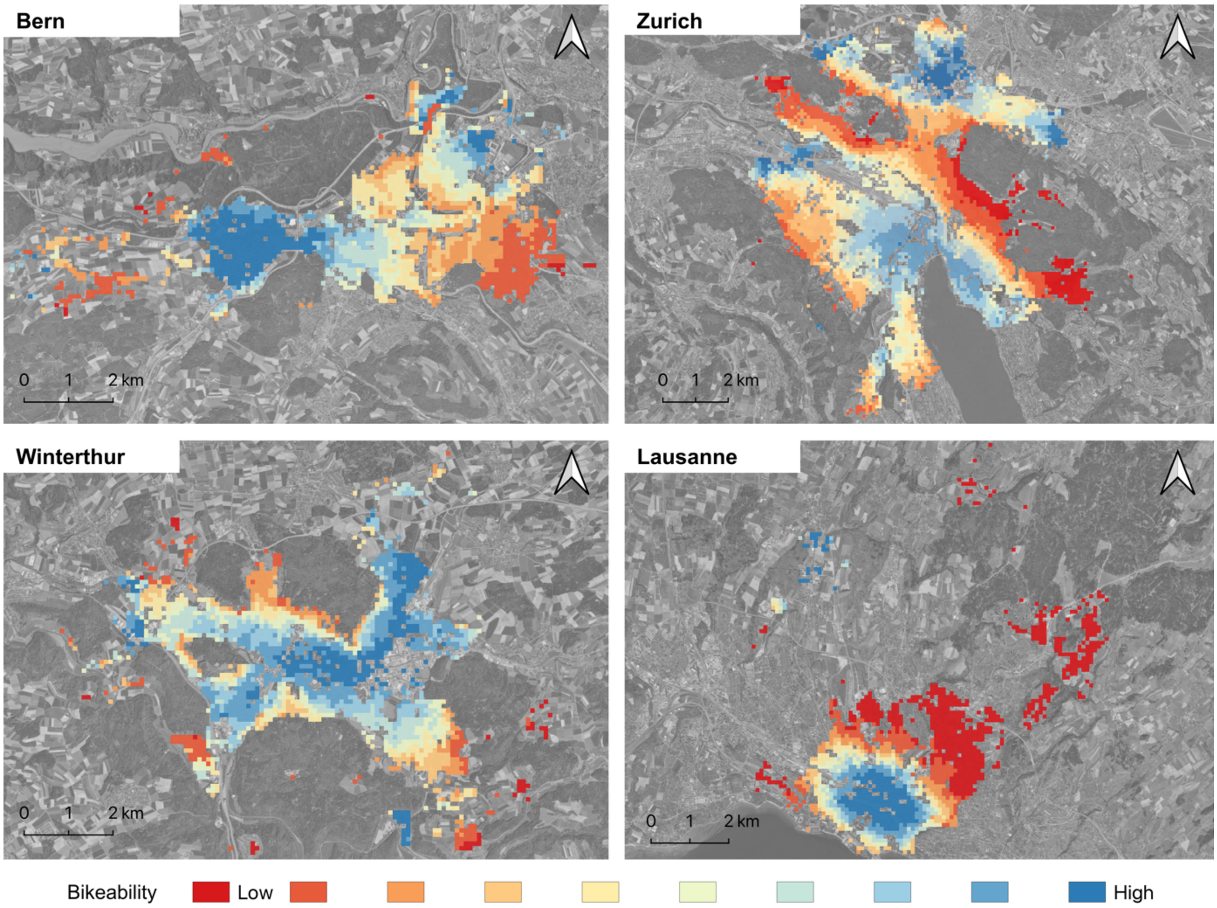


Figure 21 Index deciles for bikeability to train stations.

The deciles of the total bikeability index are presented in Figure 22. The total bikeability index describes the general traffic coverage quality by bike, integrating bikeability to the different destination types into one measure. Bikeability tends to be relatively high in the city centers, where destination density is high. This is particularly true for Lausanne. However, moving away from the city center does not automatically imply lower bikeability. For example, bikeability is high in Seebach and Oerlikon in Zurich, or in Bümpliz and Bethlehem in Bern.

In the city of Bern, the areas with high bikeability clusters are Bümpliz, Bethlehem and the city center (Innere Stadt). Whereas the city center has a particularly high destination density, Bümpliz and Bethlehem have a high density of streets with a high BLOS. They have a high density of traffic calmed residential streets with a BLOS of B. High bikeability values can further be observed in the northeast (Breitenrain). Bikeability seems to be the lowest in the west (Oberbottigen) and in Felsenau and Tiefenau. Oberbottigen belongs to the municipality of Bern, but it is a rural area with a low destination density. The low bikeability index values in Felsenau and Tiefenau can be attributed to the streets with a low modeled BLOS leading towards the city center and its destinations. Since most network segments are flat, the contribution of the slope to the heterogeneity of bikeability values within the city of Bern is low.

Most of the values from the highest bikeability index decile are in Winterthur. Opposed to Bern and Zurich, there is one cluster of high bikeability in Winterthur. The entire core of the city belongs to the 10th bikeability index decile. The cluster in this area is in line with a high density of destinations and a flat topography. Most residential streets are traffic calmed and have a BLOS rating of B. Certain short sections of the main roads leading away from the city center have a comparably high BLOS of A or B. However, most sections on these streets are modeled with a BLOS of D or E. The share of the total network length belonging to the BLOS scores E or F is the lowest in Winterthur (10.8%). Furthermore, in Reutlingen, Guggenbühl and Oberwinterthur, bikeability is high. These areas are characterized by streets and paths with a high BLOS connecting them to the destinations towards the city center. The lowest bikeability values are concentrated on the outskirts in the southeast (Iberg) and Neuburg in the west. Bikeability in the southeast of the municipality is low, despite streets and paths with a high BLOS are leading from there towards the core of the city. The low bikeability in this area can mainly be attributed to the high actual distances to important destinations towards the center.

In contrast to Bern and Winterthur, the pattern of the bikeability index values for Zurich seems to be heavily influenced by the slope. As described in Section 5.2.2, the municipalities of Winterthur and Bern also contain hills. However, the influence of topography is more apparent in Zurich, because bikeability was calculated for populated hectares and the hills, like Zürichberg in the northeast, are more populated. Bikeability decreases with increasing height at the Zürichberg, Uetliberg and in Höngg. The low bikeability in these regions indicates that topography outweighs the effect of green areas nearby. Comparably low bikeability values can further be found in Wipkingen and Unterstrass. These areas are characterized by a low BLOS of streets connecting them to other neighborhoods. The high bikeability around the lake basin, in Altstetten and Oerlikon is probably caused by relatively low slopes in these regions and many destinations nearby. Bikeability is high, although these areas have a comparably high density of streets with a BLOS of D or lower.

The bikeability index values in Lausanne are low compared to the other three cities. Only a few of the highest 20% of the values are in Lausanne, whereas the majority of the lowest bikeability index decile is in Lausanne. The highest values are concentrated in the center, where a lot of destinations are nearby. In the northeast, towards Vers-chez-les-Blancs, there is a cluster of values from the lowest decile. The main road leading from the center to the northeast has the lowest BLOS score F. In general, most main roads in the municipality have a low BLOS rating of D or lower. The share of the total network length belonging to the BLOS scores E or F is the highest in Lausanne (16.3%). Because of this fact and the high slopes evenly distributed within the municipality, bikeability values are lower compared to the other cities. The high BLOS and comparably low slopes of the footways along the lake are not fully captured by the index since almost no population point is present in this area. Therefore, only a few routes lead through these footways with a high bicycle suitability.

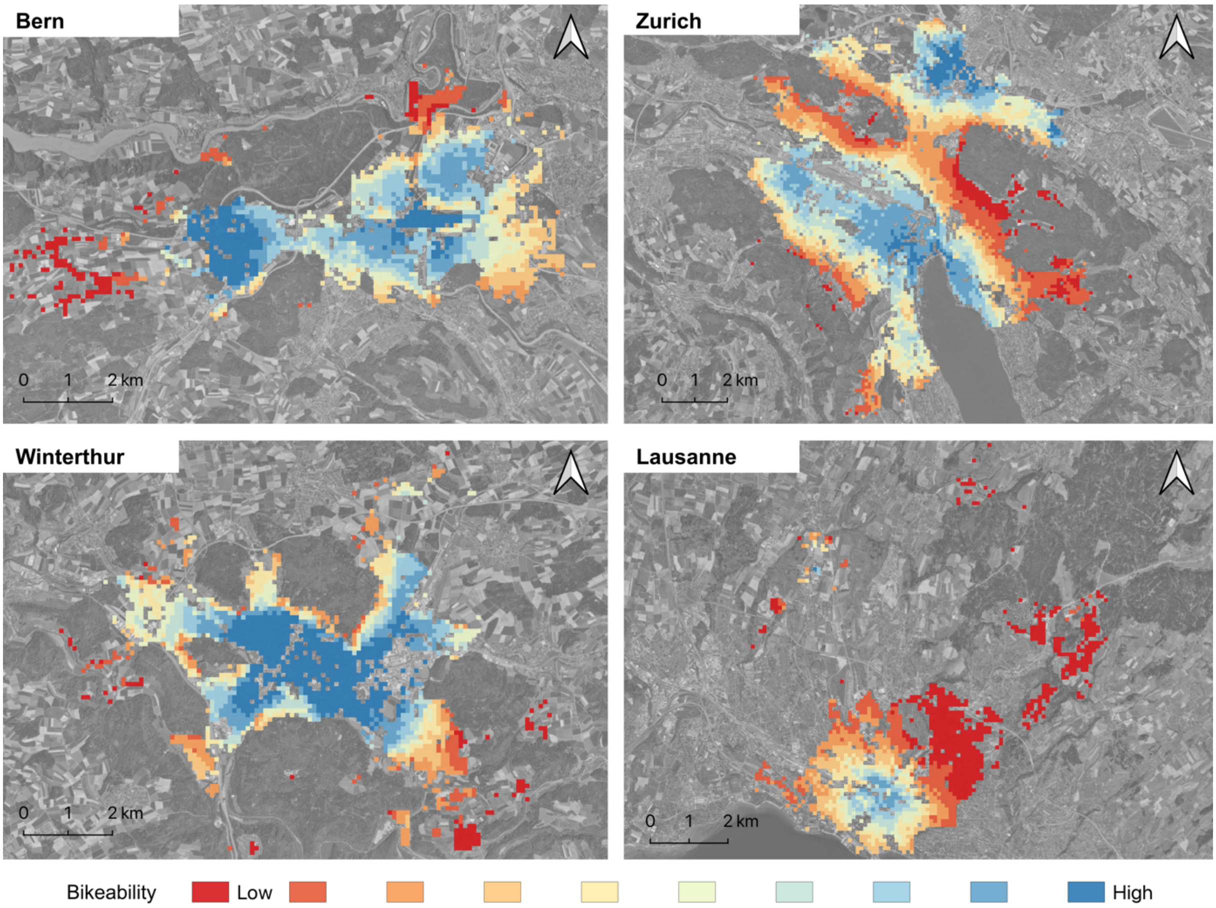


Figure 22 Total bikeability index deciles.

The distribution of the bikeability index values for the four cities in Figure 23 supports the findings from the bikeability maps in Figure 22. The highest values are concentrated in Bern and Winterthur, whereas the lowest values are concentrated in Lausanne. In Bern and Winterthur, there are only a few values below 0.2. In Lausanne, however, 0.2 is roughly equal to the median of the bikeability index values. The values in Winterthur seem to be roughly normally distributed around the median. In Zurich, the highest values are distributed closely above the median, the range of values below the median is longer. If the cities are ranked according to the median bikeability index value, the order with decreasing bikeability is as follows: Bern, Winterthur, Zurich and Lausanne. With a value of 0.3151 for Bern and 0.3148 for Winterthur, the two cities almost have an equal median index value. These two cities are followed by Zurich with a median index value of 0.2845. The largest gap in the median bikeability index value is between Lausanne (0.2018) and the other three cities.

Figure 23 Violin plots of the bikeability index values for the four cities Bern, Lausanne, Winterthur and Zurich.

The results of the sensitivity analysis with bike accidents, described in Section 4.4.4, are shown in Figure 24. The whole workflow to calculate bikeability per populated hectare raster cell was repeated, except that for the cost distances in the gravity-based approach, an additional cost factor was introduced depending on the number of bike accidents per network segment. The sensitivity analysis with the number of bike accidents allows to see to what degree the results of the bikeability index change, if objective safety is additionally considered. The spatial distribution of the bikeability index values in the four cities considering this additional cost factor is very similar to the one of the total bikeability index in Figure 22. The pattern of the index deciles is very stable. However, since an additional cost factor is introduced, the decile of a few single raster cells slightly changes. Because of the inclusion of an additional cost factor, the variation of the bikeability index values is less gradual compared to the total bikeability index. A slightly less smooth variation of bikeability index deciles can, for example, be observed in the northeast in the city of Bern (Breitenrain). With the total bikeability index in Figure 22, the largest part of this neighborhood belongs to the second highest index decile. Additionally accounting for the number of bike accidents leads to the fact that only a few raster cells belong to the second highest decile. Figure 35 and Figure 36 in Appendix C show that the index value distribution looks the same as for the total bikeability index (in Figure 23) and that the index values increase just by a few percentages.

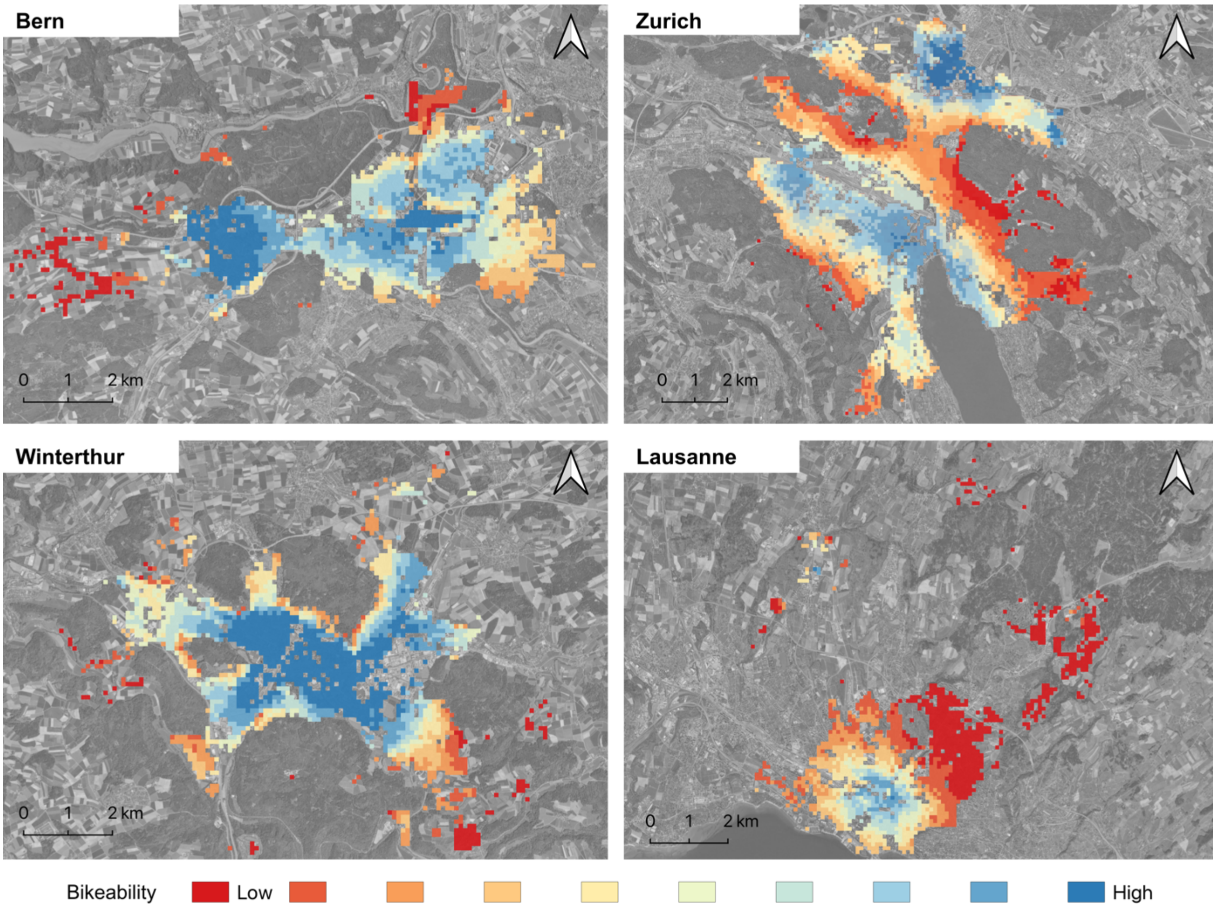


Figure 24 Total bikeability index deciles with number of accidents additionally included for the calculation of the cost distances.

5.4 Effect of bicycle infrastructure on bikeability

The results of the bikeability index are heavily dependent on the actual distances to destinations. For policymakers, another interesting question is, however, which areas are most in need of potential improvements to the bicycle infrastructure. To isolate the effect of bike infrastructure on bikeability, the mean distance to reachable destinations (within the threshold travel distance of 4 km) with distances scaled by the BLOS was compared to the actual mean distance for each hectare raster cell. The higher the percentage change in mean distance with perceived distances using BLOS compared to the actual distances, the more are people deprived of suitable bike infrastructure to reach important destinations. For example, a change of 15.0% indicates that the mean distance increases by 15.0% using the perceived distances depending on BLOS compared to the actual distances. Figures 25-28 show the change in mean distance per populated hectare raster cell for each city individually.

In the city of Bern, the highest increases in mean distance are in Oberbottigen and Felsenau/Tiefenau. These neighborhoods have streets with a low BLOS connecting them to destinations towards the center. Furthermore, despite a high density of traffic calmed residential streets in Spitalacker and Elfenau-Brunnadern with a BLOS of B, the increase in mean distance is relatively high in these regions. This indicates that the main roads connecting these areas to other neighborhoods in the city are of a low cycling quality. The increase in distance is low in Bethlehem, where also roads connecting it to other neighborhoods have a relatively high BLOS.

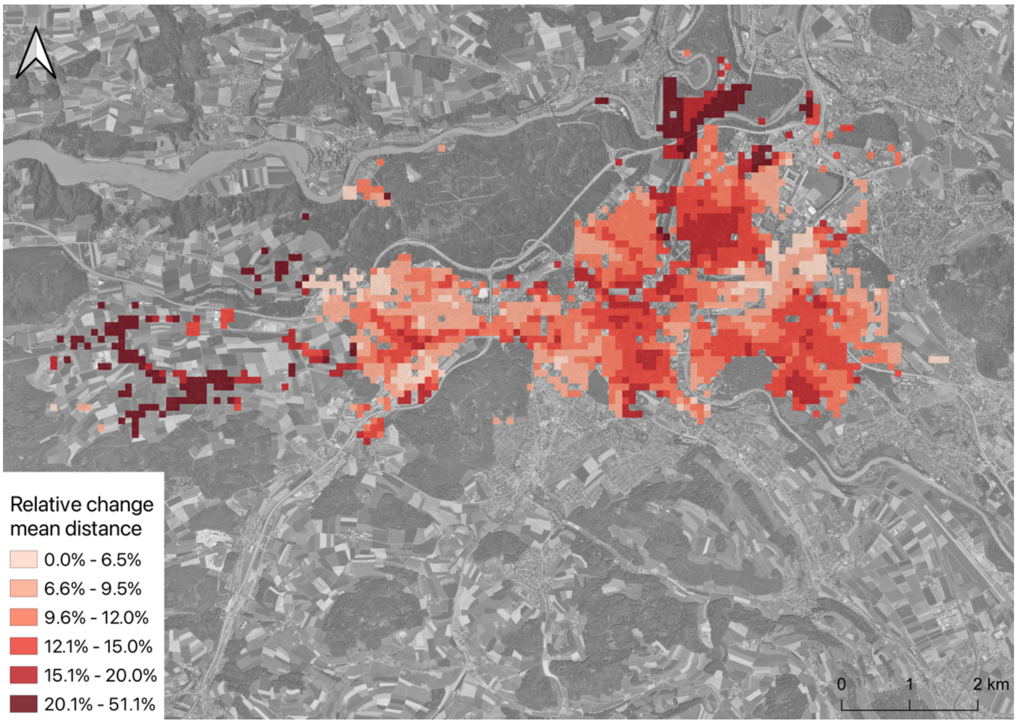


Figure 25 Change in mean distance to destinations for the city of Bern.

As it becomes evident from Figure 26, the lowest values in Lausanne tend to be towards the municipality border in the east, west and in La Sallaz. These are areas with a high density of residential streets. Most deprived of suitable bike infrastructure on routes to important destinations are people living in Vers-chez-les-Blancs, Montheron and Vernand. The main connections from these regions towards the city center have a low BLOS of E or F. A high density of streets with a BLOS of E can be found in Chauderon and Montoie, leading to a relatively high increase in mean distance in these regions.

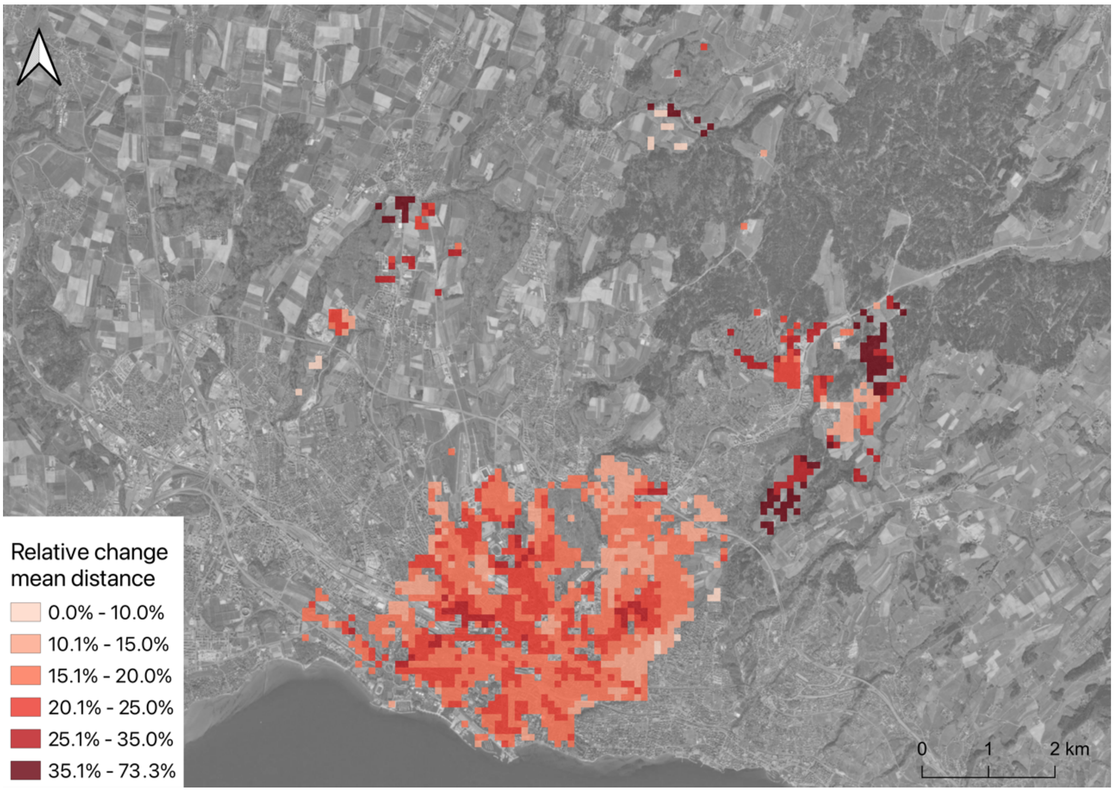


Figure 26 Change in mean distance to destinations for the city of Lausanne.

In Figure 27 for the city of Winterthur, there are some hectare raster cells for which the mean distance to destinations is lower with the perceived distances considering BLOS compared to the actual distance (colored in blue). The routes from these locations to destinations therefore consist of network segments with a BLOS of A (cost factor of 0.8). Such areas can be identified in Guggenbühl in the northeast, and Sennhof and Iberg in the southeast. The values in Sennhof and Iberg indicate a high cycling quality of the network segments leading to the city center. The low bikeability values in this region in Figure 22 are therefore attributable to the low actual spatial accessibility. Locations from where streets have a low cycling quality to reach important destinations can be identified in the west of Wülflingen and in Schlosshof. Neuwiesen, the region in the west of the main station, is another area for potential improvements in terms of bike infrastructure. Neuwiesen has a high density of traffic calmed residential streets with a BLOS of B, but the main roads leading to other neighborhoods have a BLOS of D or E.

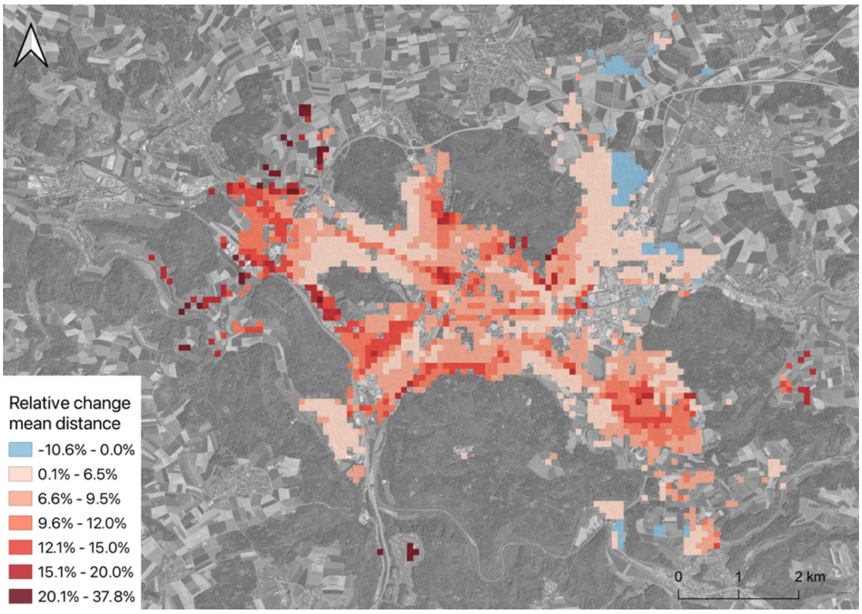


Figure 27 Change in mean distance to destinations for the city of Winterthur.

In Zurich, locations from where relatively suitable bike infrastructure is provided are in Wollishofen, Tiefenbrunnen, Höngg and Schwamendingen (compare Figure 28). The relatively low increase in mean distance for Höngg further indicates that the comparably low bikeability values in Figure 22 are mainly attributable to the topography and not the bike infrastructure. People living in Oerlikon, Hottingen, Albisrieden and Wipkingen are relatively deprived of suitable bike infrastructure. Particularly in Oerlikon and the city center, the density of streets with a BLOS of E is relatively high. Albisrieden and Wipkingen do not consist of a particularly high density of streets with a low BLOS, but the main road axes to other neighborhoods have a low BLOS.

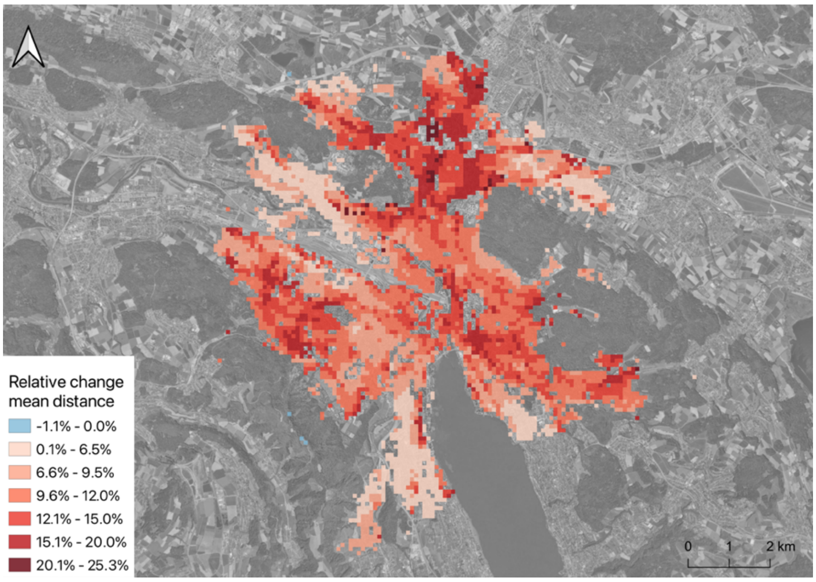


Figure 28 Change in mean distance to destinations for the city of Zurich.

6 Discussion

The objective of this chapter is to discuss the research questions presented in Section 1.2 in the context of the literature and the results of the analysis in Chapter 5. In Sections 6.1 and 6.2, the two research questions are critically discussed. The limitations of the study are mentioned in Section 6.3. Starting points for further research are outlined in Section 6.4.

6.1 Bikeability index

RQ1: How does the level of bikeability compare within and between different Swiss cities?

The developed bikeability index was used to address the first research question of this project. The index allows to investigate how bikeability varies within and between different Swiss cities. It shows for each populated hectare raster cell the comfort and convenience to reach important destinations by bike (rating from low to high bikeability using the index deciles under the consideration of all case study areas). The integration of perceived distances between origins and different types of destinations in the gravity-based bikeability calculation allows to use the index as a measure of the traffic coverage quality by bike. The index can therefore be used as an indicator describing the micro location of buildings or neighborhoods in terms of cycling quality. It can be used for site evaluations and to compare the cycling quality of different locations. Given the positive influence the cycling quality of the built and physical environment has on cycling uptake, the measure can further be used to describe an indirect dimension of the sustainability of residential buildings.

The implemented gravity-based bikeability index allows to investigate within- and between-city variation simultaneously. Previously developed bikeability indices mainly focus on one specific city or neighborhood (Grigore et al., 2019; Krenn et al., 2015; Wysling and Purves, 2022). Studies aiming to compare the cycling quality of different cities mainly rely on the concept of bike friendliness and not bikeability. They are further often based on surveys and not the analysis of (spatial) data, not allowing to capture how cycling quality varies within a city (Copenhagenize, 2019; Pro Velo Schweiz, 2022).

The index was applied to four different Swiss cities: Bern, Lausanne, Winterthur and Zurich. However, the chosen approach and the used data with nationwide coverage ensure that it can be easily applied to other urban areas in Switzerland to describe traffic coverage quality by bike. In the trade-off between level of detail and transferability (Hardinghaus et al., 2021), the developed index focuses on the latter. Only factors for which data with nationwide coverage are commonly available were included in the bikeability index. In contrast, Grigore et al. (2019) use data provided by the canton of Basel or factors for which data had to be manually introduced, limiting the transferability of the index to other urban areas in Switzerland. Nevertheless, they are able to consider a larger variety of factors influencing cycling quality with a high level of detail for their case study area in the city of Basel. For example, their implemented index accounts for the width of bike infrastructures, potential hazards like longitudinal car parking, or the share of heavy traffic.

The perceived distances in this project were used to consider the cycling quality of the built and physical environment on the routes between origins and destinations. Factors considered for the calculation of the perceived distances were the type of bike infrastructure, the speed limit, the slope and the surrounding natural environment. The speed limit and the type of bike infrastructure were combined into a BLOS rating. According to Pucher and Buehler (2008), these two factors are most important to make cycling safe and comfortable. Because of data limitations, other factors influencing cyclists' travel behavior could not be considered in this project. Data limitations are a critical issue in the development of bikeability indices (Castañon and Ribeiro, 2021). For example, the quality of intersections, traffic volumes and the quality of bike infrastructures could not be considered. As illustrated in the literature review in Section 2, intersections are a source of delay and conflict for cyclists (Broach et al., 2012; Dill and McNeil, 2013). Traffic volumes strongly affect the perceived safety and comfort of cyclists (Broach et al., 2012; Sener et al., 2009). The speed limit was included in the analysis since the perceived safety of cyclists decreases with increasing speeds of motorized traffic, but it was further assumed to be an approximation for traffic volumes. The speed limit and traffic volume are certainly correlated (Wysling and Purves, 2022). Nevertheless, a high speed limit does not automatically imply a high traffic volume. The BLOS of the roads in the rural area in the west in the city of Bern, for example, is probably too low because the traffic volume is overestimated based on the high speed limit. Along with the speed limit, the BLOS modeling only considered the type of bike infrastructure. The quality of bike infrastructure could not be considered, even though it influences the cycling experience (Mueller et al., 2018). Following the Netherland's bike infrastructure manual, bike infrastructures should be adequately implemented fulfilling the five requirements: Safety, cohesion, directness, comfort and attractiveness (CROW, 2016).

If such data are available, one could, for example, additionally account for the width of bike lanes.

Since the final goal of the analysis was to describe the general traffic coverage quality by bike, the analysis was not restricted to one destination type. Most bikeability studies focus on one destination type, particularly on workplaces (Hamidi et al., 2019). Bikeability was first calculated for each destination type separately before the destination type specific values were integrated into a total bikeability index through a weighted summation, following the concept of integrated spatial accessibility (Ashik et al., 2020). The included destination types were selected based on the national law on cycle paths and the Swiss bike manual: Train stations, leisure and sports facilities, public parks, hospitals, schools and grocery stores. Since the case study areas are relatively small and the destinations were limited to the mentioned types, processing times were still manageable with the destinations included as raw POIs in the routing calculation. Other studies dealing with a larger case study area and a higher density of POIs (e.g., additionally including restaurants and bars) have aggregated the POIs on a regular grid (Iacono et al., 2010; Mekuria et al., 2012). For example, Wysling and Purves (2022) count the number of POIs per cell of a regular grid for their bikeability index in the city of Paris. The number of POIs per grid cell can be used as an activity potential factor in the gravity-based bikeability index calculation. Similarly, Lowry et al. (2012) use the square footage of commercial destinations as an attractiveness factor. In this project, only for train stations a weight was introduced, depending on its level of service. With the introduction of weights in the calculation, it could be avoided that a small train station is treated equally as a city's main station. For the other destination types, no attractiveness factor was introduced. The attractiveness of public parks, for example, does not depend on their size, but rather the landscape quality and their features (Kaczynski et al., 2008; Mao et al., 2022).

It is further expected that the data quality of the different types of POIs affects the bikeability calculation differently. As described in Section 5.1, some types of destinations are more evenly distributed in the case study areas compared to others. For example, grocery stores are more evenly distributed than train stations. Since the definition of train stations is vague and for the grocery stores OSM was used as the data source, some POIs of the two destination types might be missing in the data. However, because of the even distribution, a missing grocery store is expected to affect bikeability at a location less severely compared to a missing train station.

For the origins in the bikeability calculation, the centroids of the populated hectare raster cells were used. This comes with the advantage that the bikeability index is calculated with a relatively high resolution and can directly be linked to the residential population for further analyses. The populated hectare raster should be the prior level of analysis for measures describing traffic coverage quality in Switzerland (UVEK, 2015). A 100 x 100 m raster was also used for bikeability indices developed by Codina et al. (2022), Grigore et al. (2019) and Krenn et al. (2015). Other studies used larger raster cell sizes, particularly to reduce processing times (Wysling and Purves, 2022). With the size of the case study areas and the number of POIs in this project, processing times were, however, still manageable using the populated hectare raster. Opposed to a regular grid fully covering the whole case study area, some parts of the bike network may not be captured by the bikeability index calculated on populated grid cells. The footways with a high bicycle suitability along Lake Geneva in Lausanne, for example, are not adequately considered in the bikeability calculation. There are almost no population points present in this area, from which routes are calculated (compare Section 5.3).

In general, it is important to note that the results of a bikeability index are influenced by the MAUP (modifiable areal unit problem). The outcome of an analysis varies depending on the spatial unit the bikeability index is calculated (Vale et al., 2016). The MAUP introduces two distinctive effects: A scale effect and a zoning effect (Clark and Scott, 2014). The scale effect arises when the results vary depending on the chosen spatial scale (resolution). With the populated hectare raster in this project, the bikeability index can directly be linked to the population, but it further models bikeability in a high level of detail to see local variations. Using neighborhoods or a grid with a lower spatial resolution as the level of analysis might obscure local variations that are visible using the hectare raster. The zoning effect describes that the analytical results of a fixed level of spatial resolution depend on the extent of the used zone (Clark and Scott, 2014). The zones in this analysis, the municipalities, are partly arbitrary in terms of the urban continuum. The urban continuum of a city might end before or extend beyond its municipality borders (Codina et al., 2022). The comparison of bikeability in Chapter 5 is based on all populated hectare raster cells within the municipalities. Therefore, the rural area in the west of the municipality of Bern, for example, is included in the comparison of the different cities. If this rural area was not part of the municipality, there would be less low index values in Bern. However, the goal of the analysis was to evaluate bikeability in terms of the residential population on the political level of municipalities.

For the definition of the relative importance of the different destination types and the cost multipliers for the perceived distances, travel surveys and previous literature were used as good as possible. Nevertheless, for parameters for which no value was provided, a value had to be assumed. Particularly the determination of the travel impedance factor (β) in the gravity-based calculation had to be assumed based on the distribution of bike trip lengths in Switzerland. Furthermore, the threshold travel distance of 4 km was used for all different destination types. On the contrary, one could define a destination type specific maximum travel distance and travel impedance parameter (Ashik et al., 2020; Saghapour et al., 2017). The willingness to cycle with increasing distance is expected to vary between different destination types (BFS and ARE, 2023). To keep the method simple and because values for all destination types individually were not available, one travel impedance factor and threshold travel distance were chosen in this project.

The four case study areas of this project can be ranked from high to low bikeability as follows if the median bikeability index value is considered: Bern, Winterthur, Zurich and Lausanne. This order is in line with the trip-based bike modal share of the different cities (compare Section 3.1.3). In 2021, the bike modal share was the highest in Bern (16%), followed by Winterthur (15%) and Zurich with 13% (Städtekonferenz Mobilität et al., 2023). With the most recent data available, the bike modal share was the lowest in Lausanne with 2% in 2015 (Ville de Lausanne, 2023a). As described in Section 3.1.3, Bern and Winterthur are also on top of the ranking in the "Prix Velo", whereas Zurich and Lausanne are at the bottom of the ranking for the largest Swiss cities (Pro Velo Schweiz, 2022). However, in the "Prix Velo" ranking the order of the cities is switched at both ends of the ranking compared to the ranking using the median bikeability index value. Winterthur is first, Bern second, Lausanne ninth and Zurich tenth. However, it is important to note that the median bikeability index value is almost equal for Bern (0.3151) and Winterthur (0.3148). The difference between the two rankings is that the "Prix Velo" measures bike friendliness based on surveys among the population, and the developed index describes bikeability based on spatial data. The "Prix Velo" considers, for example, factors such as bike policies (Pro Velo Schweiz, 2022). In contrast to the "Prix Velo", the developed bikeability index considers the topography and the actual network distances to destinations, and therefore the general urban morphology (i.e., if parts of a city are separated by a river or a lake). The gap in median bikeability index value is larger between Lausanne and Zurich than between Zurich and Winterthur. A large share of the gap between Lausanne and Zurich probably is attributable to the topography. Moreover, the gap between Bern and Zurich is anticipated to be larger, if just the urban core of a municipality was considered. Without the rural area in Oberbottigen, there would be less low bikeability index values in Bern.

As other traffic coverage qualities, like the public transport quality classes in Switzerland, the developed bikeability index describes a potential. It can be used as a propensity to cycle tool for home-based trips with a utilitarian purpose. The actual use of bikes, however, further depends on the characteristics of individuals, like their attitude. Since it describes a potential, a comprehensive validation of the developed bikeability index was beyond the scope of this project. Above it was shown that the median bikeability index value of the four case study areas follows the same order as the trip-based bike modal share. However, it would further be interesting to see to what degree the bikeability index correlates with regular cycling trips within a given city. In general, only a few bikeability studies have validated their indices (Castañon and Ribeiro, 2021). A validation was conducted by Codina et al. (2022) for their bikeability index in Barcelona, Spain using a travel survey. They find that the level of bikeability (calculated on a 100 x 100 m raster) is highly associated with the frequency of cycling. The index can reliably predict the frequency of bike use.

The factors included in the bikeability index capture the perceived safety, comfort and convenience for cyclists. Previous studies have shown that it is rather perceived safety than objective safety that influences cyclists' travel behavior (von Stülpnagel and Rintelen, 2024). In some situations, cyclists systematically underestimate crash risk. Nevertheless, objective and subjective safety are mostly well aligned (Hull and O'Holleran, 2014; von Stülpnagel et al., 2022). To see how the results change, if objective safety is additionally included, a sensitivity analysis was conducted using bike accidents. The number of bike accidents per network segment was used to define an additional cost factor for the cost distances in the bikeability calculation. The results in Section 5.3 revealed that the distribution of the bikeability index values is very similar in the four case study areas if bike accidents are additionally considered, compared to the total bikeability index. The almost identical results were one reason why the number of bike accidents was not included in the final bikeability index. Moreover, since data on cycling volume per network segment were missing, exposure could not be accounted for. Alternatively, one could model bicycle ridership per network segment as done by Özvegyi

(2023), when data on cycling volume are lacking. However, the implementation of such a model for all four case study areas exceeded the scope of this project. Previous studies have shown that one should account for exposure, i.e., one should use the relative frequency of bike accidents and not the absolute number. The use of absolute numbers can produce a misleading picture of the provided safety (Kamel et al., 2020; von Stülpnagel et al., 2022). Bike accident statistics further severely underestimate the actual number of cycling incidents (Juhra et al., 2012). The bike accident statistics used for the sensitivity analysis only include accidents with personal injury (ASTRA, 2023b). Dangerous situations not leading to an injury are important for the experience of cyclists and influence cycling uptake (Aldred, 2016). Non-injury incidents where cyclists must take direct action to avoid collisions with vehicles are referred to as near misses in the literature (Aldred, 2016; Sanders, 2015).

6.2 Improvements of bike infrastructure

RQ2: Which areas are comparably most in need of improvements to the bicycle infrastructure?

Considering the distance to destinations and the routes' quality, the gravity-based bikeability index is a useful measure to describe traffic coverage quality by bike. However, for policymakers it is further important to identify areas for improvement in terms of bike infrastructure. In this case, the bikeability index is not a well-suited measure. The developed bikeability index considers the type of bike infrastructure and the speed limit, but the index values are highly dependent on the actual distance to destinations, and further influenced by the topography and the natural environment. For example, a location with three very close destinations within the set threshold travel distance still has a high bikeability index value, even if the BLOS of the streets to these nearby destinations is low. The perceived distances are calculated based on the short actual distances, still resulting in relatively short distances. To show where improvements of bike infrastructure are most relevant and therefore to address the second research question of this project, another measure was introduced.

Similarly to Grigore et al. (2019), the mean distance to destinations with perceived distances only considering BLOS was compared to the mean distance using the actual distances (compare Section 5.4). Grigore et al. (2019) scale the actual distances to destinations in the case study area, such that their average distance is equal to the average perceived distance using BLOS. The difference in meters between the two values is then used as a measure of cycling quality. In contrast, the percentage change in mean distance using the perceived distances scaled by BLOS compared to the mean distance using the actual travel distance to all destinations within the threshold travel distance of 4 km was calculated for this project. The percentage change in mean distance allows to isolate the effect of bike infrastructure on reaching important destinations by bike. The measure controls for the actual distance to destinations and excludes the topography and green and aquatic areas from the analysis. Compared to raw changes in mean distance (e.g., in meters), the percentage change allows to account for different base travel distances. It makes a difference, if the mean distance increases by 100 meters from a base travel distance of 3000 meters or 500 meters.

With BLOS, network segments with a poor cycling quality can be identified (see Figure 18). However, it does not capture where improvements are most relevant. In contrast, the percentage change in mean distance is based on the shortest route between origins and destinations. It therefore considers the choices cyclists can make on routes to reach destinations. It shows where people are relatively deprived of suitable bike infrastructure to reach important destinations. For example, if a cyclist can choose between two routes of an almost equal length, where one has a high BLOS and one a low BLOS, the percentage change in distance is low. With an improvement in BLOS along the route with the lower BLOS, the benefit for cyclists is limited since there already is a parallel route with a high BLOS and similar length. Similarly, the routes calculated for the change in mean distance capture if a street with a low BLOS is the only connection available between an origin and a destination. Locations with such a connection to their destinations receive a relatively high percentage change in distance to destinations.

As observed in Section 5.4, areas providing a relatively high BLOS on routes to destinations are not located in the city centers, but rather towards the outskirts of the case study areas. These areas either have a relatively high density of segments with a high BLOS or a main connection to the city center with a relatively high BLOS. Compared to people living in those areas, people living in the city centers tend to be relatively deprived of suitable bike infrastructures to reach important destinations. The relationship was not investigated in further detail, but this coincides with the fact that most cities have difficulties implementing bike infrastructures in densely built areas where street space is scarce (Di Mascio et al., 2018). In these areas, bike infrastructures must be integrated into existing road networks (Parkin and Koorey, 2012). The implementation of bike infrastructure physically separating cyclists is often only possible at the expense of other modes of transport. On the outskirts in less densely built areas, in contrast, separate bike infrastructures can be installed more easily. However, there are also city centers with a structure better suited for cycling. For example, the typical wide boulevards in Paris provide plenty of street space in the densely built city (Wysling, 2021).

The percentage change in mean distance indicates where people are relatively deprived of suitable bike infrastructures to reach important destinations. The measure can therefore be a useful tool for policymakers to prioritize in a first step, in which areas improvements of bike infrastructure are most relevant. In a second step, the modeled BLOS could be used to support the identification of potential locations for improvement on the level of network segments. If cycling should be safe and desirable for a broad spectrum of the population, particularly for "Interested but Concerned" types of cyclists, adequate bike infrastructure needs to be implemented (Buehler and Pucher, 2021; Dill and McNeil, 2013). Given the strong consensus in the literature that cyclists prefer traffic calmed streets with reduced speed limits or infrastructures physically separating cyclists from motorized traffic, implementations of bike infrastructure should predominantly focus on streets with high speed limits, not providing separate bike infrastructures. Streets with such characteristics were modeled with a BLOS of E or F. Streets with a BLOS of E have a speed limit of 50 km/h not providing any bike infrastructure or a speed limit of 60-80 km/h with infrastructures not physically separating cyclists from motorized traffic (shared bus lanes or cycle lanes). The lowest BLOS score F indicates streets with a speed limit of 60-80 km/h not providing any bike infrastructure. However, due to potential data inaccuracies in the type of bike infrastructure in OSM (see Section 6.3), the identified network segments should further be examined individually. Since the quality of infrastructures could not be considered (i.e., their layout), it is further important that network sections with a relatively high BLOS are not completely neglected for potential further improvements of bike infrastructure. Street segments might have a high BLOS because they provide a suitable type of bike infrastructure, but the quality of the infrastructure does not provide enough safety and comfort for a broad spectrum of the population.

6.3 Limitations

Of course, the bikeability analysis described in this thesis has several limitations. One limitation is related to the data quality of the bike network and bike infrastructure data. Since suitable OGD were missing, OSM was used as a data source for the bike network and bike infrastructure data (compare Section 3.2). Previous studies consider OSM as a valuable data source for cycling, particularly for multicity studies (Ferster et al., 2020; Hochmair et al., 2015). However, no sources on the assessment of the quality of bike infrastructure data in OSM for Switzerland could be found. An own quantitative assessment of the data quality for the case study areas was further beyond the scope of this project. The data quality of the bike infrastructure in OSM was only assessed qualitatively for some random network sections in the four case study areas using maps and bike infrastructure plans provided by the four cities as a comparison. According to the International Organization for Standardization (ISO), the quality of spatial data is comprised of five components: Completeness, logical consistency, positional accuracy, temporal accuracy and thematic accuracy (ISO, 2013). Positional accuracy and completeness are expected to be less of a concern. For the purpose of this analysis, the network segments do not have to be recorded to the centimeter in OSM. From the sanity check of the bike networks described in Section 4.2 and the dense bike networks, it can further be concluded that the networks have a high degree of completeness.

Potential issues in data quality are mainly anticipated concerning logical consistency, temporal accuracy and thematic accuracy. In general, the random checks of bike infrastructure data did not reveal any significant problems in data quality, particularly no significant differences between the different case study areas. The implicit assumption for the between-city comparison that the data quality is similar between the case study areas therefore seemed reasonable. Nevertheless, some inconsistencies and inaccuracies were detected. An example of a qualitatively assessed logical inconsistency was described in Section 4.3.1. In all cities, some cycle tracks were not captured as an attribute of the road with a speed limit, but separately as a *highway=cycleway* with no speed limit. This inconsistency for cycle tracks was also reported by Ferster et al. (2020). A cycle track could therefore be modeled with a BLOS score of A, even though its score should be dependent on the speed limit (compare Table 4). Previous studies document that OSM data is more up to date than OGD (Ferster et al., 2020; Nelson et al., 2021). The qualitative comparison of some random network sections revealed minor inconsistencies with the bike infrastructure plans of the cities. However, for some cases it is not clear if the bike infrastructure is missing in OSM, or if the planned bike infrastructure has not been implemented yet. To reduce the risk of thematic inaccuracies, the attribute values of all OSM keys relevant to determine the bike infrastructure have been assessed. This would allow to notice, for example, misspelled words. However, no typographical errors were detected. Network sections with NA values for all OSM keys potentially describing bike infrastructures were assumed to not provide any bike infrastructure. For network sections with such NA values not providing any bike infrastructure in reality, BLOS could be modeled correctly. But if these NA values are a temporal or thematic inaccuracy, the BLOS of a network segment is underestimated. An example of a thematic inaccuracy is shown in Figure 29 for the city of Lausanne. According to the city plan on the left side of the figure, the street highlighted in blue has a cycle lane installed (red line). However, since for this street only NA values are provided in OSM for the keys relevant to model the type of bike infrastructure, it was assumed that the street has no bike infrastructure installed. With a speed limit of 50 km/h, the street was therefore modeled with a BLOS score of E (right side of the figure), although it should receive a score of D.

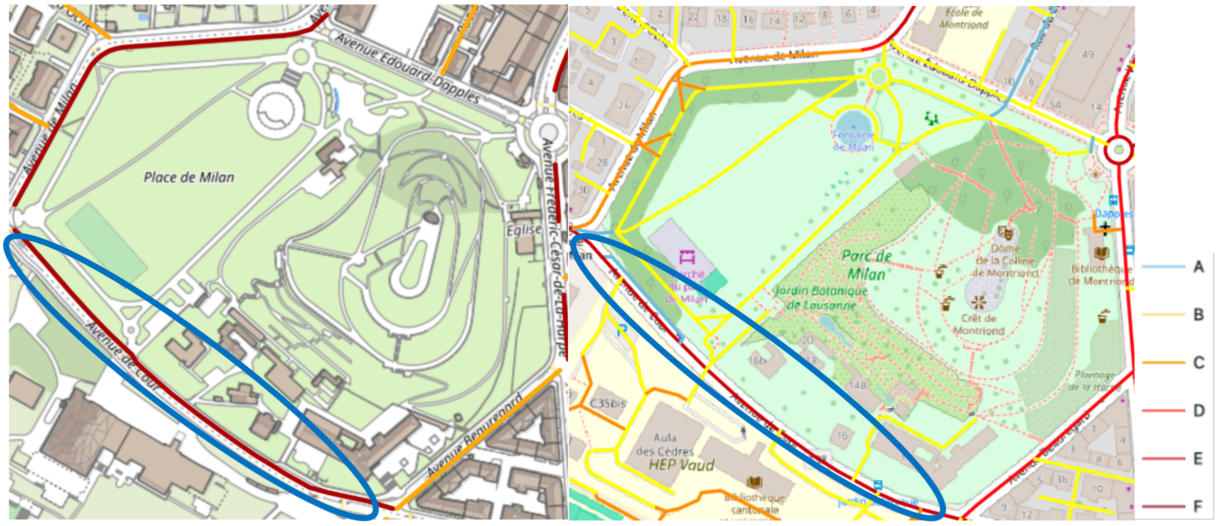


Figure 29 Thematic inaccuracy of the type of bike infrastructure in OSM for a street section in Lausanne. Left side: Screenshot from the city map with bike infrastructures provided by Ville de Lausanne (2023b). Right side: Screenshot of modeled BLOS in network.

No suitable OGD for bike infrastructure on a national level was available at the time the analysis was conducted. Nevertheless, it is expected that administrative data for bike routing and on bike infrastructure in Switzerland will be a valuable alternative to OSM data in a few years for analyses as in this project. In February 2022, swisstopo got the commission from the

Federal Council to implement the "Verkehrsnetz CH" (Swiss Transport Network). The "Verkehrsnetz CH" has the purpose to expand and optimize transport data of the public sector (Koch et al., 2022). The network is planned to uniformly represent the complete, multimodal transportation network of the country. Through the coordination of the federation, the data can be provided for free to the public, being largely uniform, complete and up to date with national coverage (Koch et al., 2022). Rules are defined to ensure the quality (i.e., completeness and up-to-dateness) of the data. In particular, the network will be routable and will provide a basis to integrally plan transportation infrastructure for the different modes of transport.

Other limitations of this project concern the model. The bike network used for the route calculation was undirected. It was assumed that cycling is possible in both directions of travel for all segments in the network. For network segments with different types of bike infrastructures in both directions of travel, the BLOS was modeled using the type of bike infrastructure leading to the higher BLOS. For example, if a road provides a cycle lane in one direction of travel and no bike infrastructure in the other direction, the BLOS of the road was modeled using the cycle lane. The goal of the routing was not to calculate fully accurate routes, but to model perceived shortest distances depending on the route choice of cyclists, modeled in previous studies. Furthermore, only destinations within the case study areas were considered, although a city's residents also cycle to destinations in neighboring municipalities. The neglect of such edge effects is an important limitation of most studies in this field (Gao et al., 2017; Vale et al., 2016). However, the implemented index mainly evaluates bikeability to public facilities and destinations for daily needs. In Switzerland, bike infrastructure policies further mainly take place at the level of municipalities (Kanton Zürich, 2021). Municipalities should enhance bikeability within their borders. Edge effects arising from POIs and bike infrastructures outside of the municipalities are therefore expected to be less of a concern for the purpose of this project.

Finally, the bikeability index focuses on home-based trips with privately owned conventional bikes. However, travel patterns are increasingly complex (Vale et al., 2016). For example, not all bike trips are round trips starting and ending at home. Furthermore, emerging phenomena in urban cycling, like E-bikes or bicycle sharing systems (BSS) are neglected in the analysis. Castañon and Ribeiro (2021) identify an absence of indicators related to these two phenomena in bikeability analyses.

6.4 Further research

Provided there is a reliable data basis, future work could include additional factors influencing cyclists' route choice in the bicycle suitability assessment, like intersections, the layout of bike infrastructures or traffic volumes. Furthermore, the index focusing on privately owned conventional bikes could be adapted or expanded to consider emerging phenomena in cycling. For example, one could additionally include locations of BSS in the bikeability index, or the cost factors for the perceived distances could be adapted for the use of E-bikes. As cycling with E-bikes requires less physical effort, the cost factors for the slope could, for example, be lowered. Bikeability could further be assessed on a regular hectare raster grid, instead of the populated hectare raster. Another interesting evaluation would be to conduct the bikeability analysis under different scenarios. One could, for example, investigate the effect on bikeability for a policy scenario in which a cycle track is provided beside all roads with a speed limit above 30 km/h in a municipality. In a few years, when the "Verkehrsnetz CH" will be available, it would further be interesting to conduct the same analysis with these OGD instead of OSM.

Future studies could further develop approaches to assess bikeability indices. One could assess the correlation between the bikeability index values on the hectare raster and the regular use of bikes (bike modal share) among the residential population. Moreover, a bikeability index that is based on a revealed preference survey using GPS data collected from cyclists in different Swiss cities would allow to determine the factors and parameters used in this study more precisely. The factors and parameters could be independently determined for the Swiss context without having to rely on studies conducted in other countries. Finally, future work could quantitatively assess the quality of bike infrastructure data in OSM for Switzerland in general, or specifically for the four case study areas of this project.

7 Conclusion

This project implemented a gravity-based bikeability index to investigate how bikeability varies within and between the Swiss cities Bern, Lausanne, Winterthur and Zurich. The index shows for each populated hectare raster cell how convenient and comfortable it is to use a bike for home-based trips. It therefore is a measure describing how prone people are to regularly use bikes to reach important destinations. Instead of focusing on one type, bikeability to different destination types was evaluated. The destination type specific bikeability indices were combined into a total bikeability index, capturing the traffic coverage quality by bike. The gravity-based bikeability index combines mere spatial accessibility with qualitative aspects of cycling. To include the cycling quality on routes to destinations, perceived distances based on the following characteristics were calculated: Type of bike infrastructure, speed limit, slope, and green and aquatic areas.

An additional analysis was carried out to isolate the effect of bike infrastructures on bikeability. Considering how bike infrastructures change the mean (perceived) distance to important destinations, it has been shown for each city where people are comparably most in need of improvements to the bicycle infrastructure. This analysis approach allows policymakers to identify areas, for which improvements of bike infrastructure are most relevant.

This project overcomes the limitation of previously implemented gravity-based bikeability indices that focus on one city as a case study area. The approach allows to investigate within- and between-city variation in bikeability simultaneously. The reliance on OSM for bike infrastructure data and OGD with nationwide coverage ensures that the developed methodology can be applied to other urban areas in Switzerland.

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Appendix

A) Overview data

Table 8 Overview of the data used for the bikeability analysis.

Data	Dataset (source)
Bike network/ infrastructure	OSM
Elevation	swissALTI3D (swisstopo, 2023b), swissSURFACE3D (swisstopo, 2023d)
Green and aquatic areas	OSM
Trees	swissTLM3D (swisstopo, 2023e)
Bike accidents	Reported bike accidents (ASTRA, 2023b)
Municipalities	swissBOUNDARIES3D (swisstopo, 2023c)
Population data (origins)	STATPOP (BFS, 2023a)
POIs (destinations)	swissTLM3D (swisstopo, 2023e), OSM, train stations (BAV, 2023b)

B) Style files OSM import

```
# Special database columns
# ========================
#
# There are some special database columns that if present in the .style
file
# will be populated by osm2pgsql.
#
# These are
#
# z_order - datatype int4
#
# way_area - datatype real. The area of the way, in the units of the
projection
# (e.g. square mercator meters). Only applies to areas
#
# osm_user, osm_uid, osm_version, osm_timestamp - datatype text. Used with
the
# --extra-attributes option to include metadata in the database. If
importing
# with both --hstore and --extra-attributes the meta-data will end up in
the
# tags hstore column regardless of the style file.

# OsmType  Tag          DataType     Flags
node,way   access      text         linear
node,way   access:conditional       text         linear
node,way   barrier      text         linear
node,way   bicycle      text
node,way   bicycle:conditional      text         linear
node,way   bicycle_road      text         linear
node,way   bridge       text         linear
```

```
node,way   cyclestreet text         linear
node,way   cycleway      text         linear
node,way   cycleway:both      text         linear
node,way   cycleway:left      text         linear
node,way   cycleway:left:oneway      text         linear
node,way   cycleway:right      text         linear
node,way   cycleway:right:oneway      text         linear
node,way   foot      text         linear
node,way   segregated      text         linear
node,way   footway      text         linear
node,way   highway      text         linear
node,way   junction     text         linear
node,way   maxspeed     text         linear
node,way   motorroad     text         linear
node,way   mob      text         linear
node,way   oneway       text         linear
node,way   oneway:bicycle       text         linear
node,way   ramp:bicycle      text         linear
node,way   route        text         linear
node,way   smoothness      text         linear
node,way   traffic_calming      text         linear
node,way   tunnel       text         linear
node,way   vehicle       text         linear
node,way   width        text         linear
node,way   z_order      int4         linear # This is calculated during
import
way        way_area     real                # This is calculated during


# Special database columns
# =======================
#
# There are some special database columns that if present in the .style
file
# will be populated by osm2pgsql.
#
# These are
#
# z_order - datatype int4
#
# way_area - datatype real. The area of the way, in the units of the
projection
# (e.g. square mercator meters). Only applies to areas
#
# osm_user, osm_uid, osm_version, osm_timestamp - datatype text. Used with
the
# --extra-attributes option to include metadata in the database. If
importing
# with both --hstore and --extra-attributes the meta-data will end up in
the
# tags hstore column regardless of the style file.

# OsmType       Tag          DataType     Flags
node,way        amenity      text         polygon
node,way        leisure      text         polygon
node,way        natural      text         polygon
node,way        tourism      text         polygon
node,way        landuse      text         polygon
```

C) Bikeability index

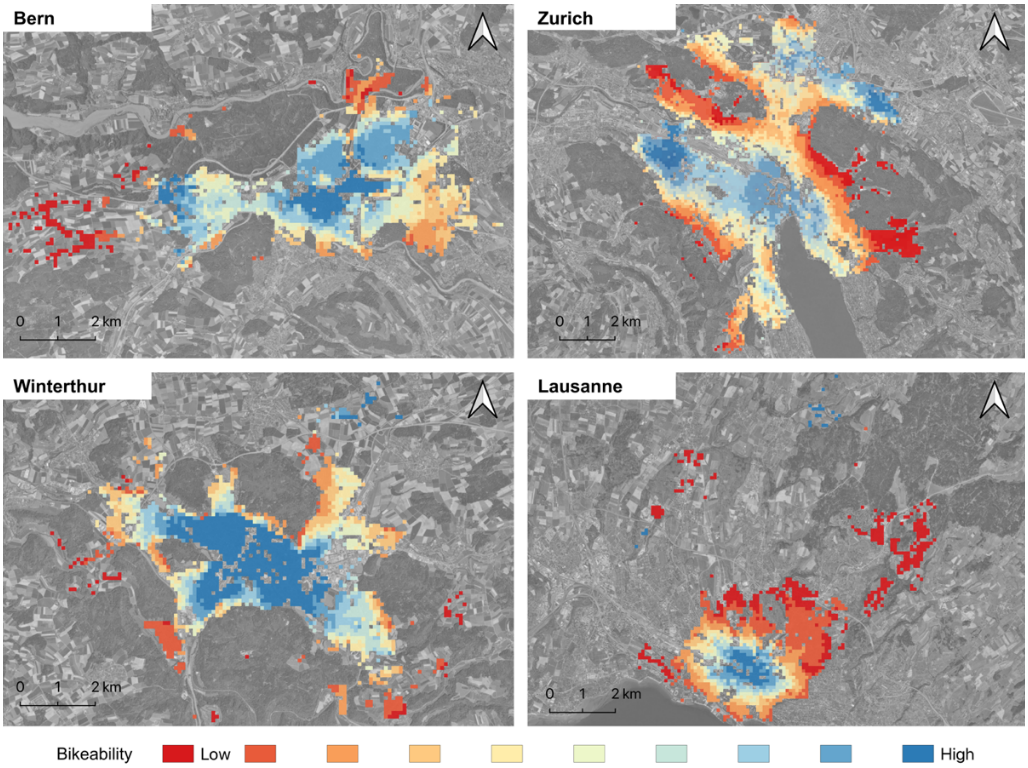

Figure 30 Index deciles for bikeability to schools providing secondary level of education.

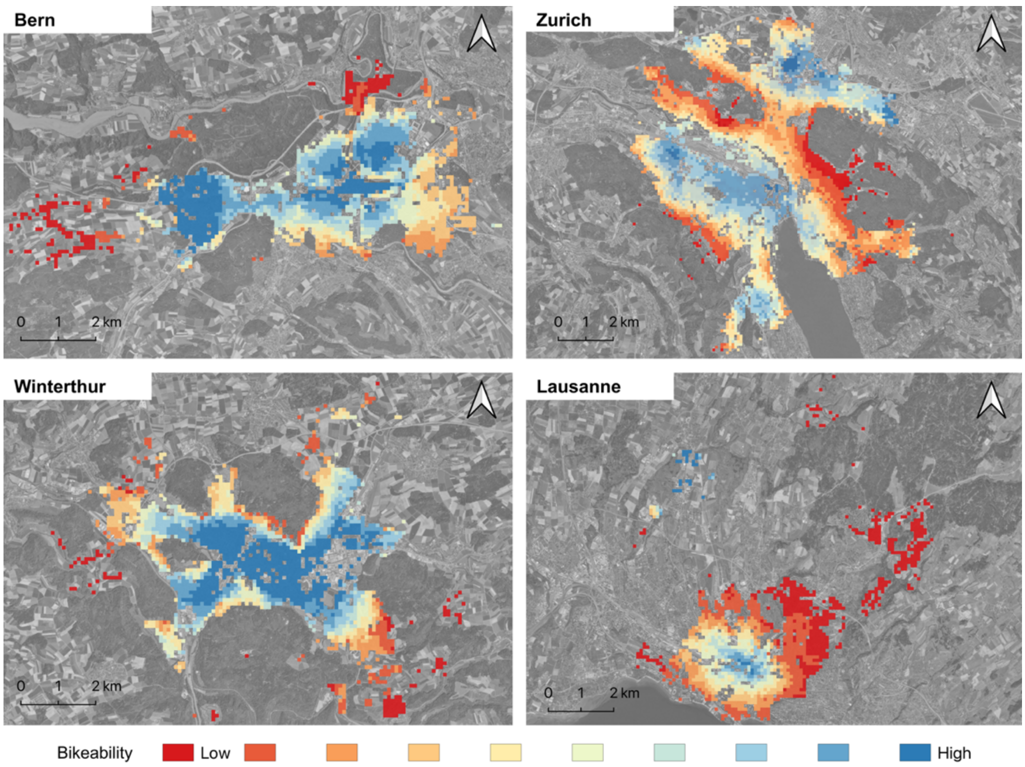

Figure 31 Index deciles for bikeability to grocery stores.

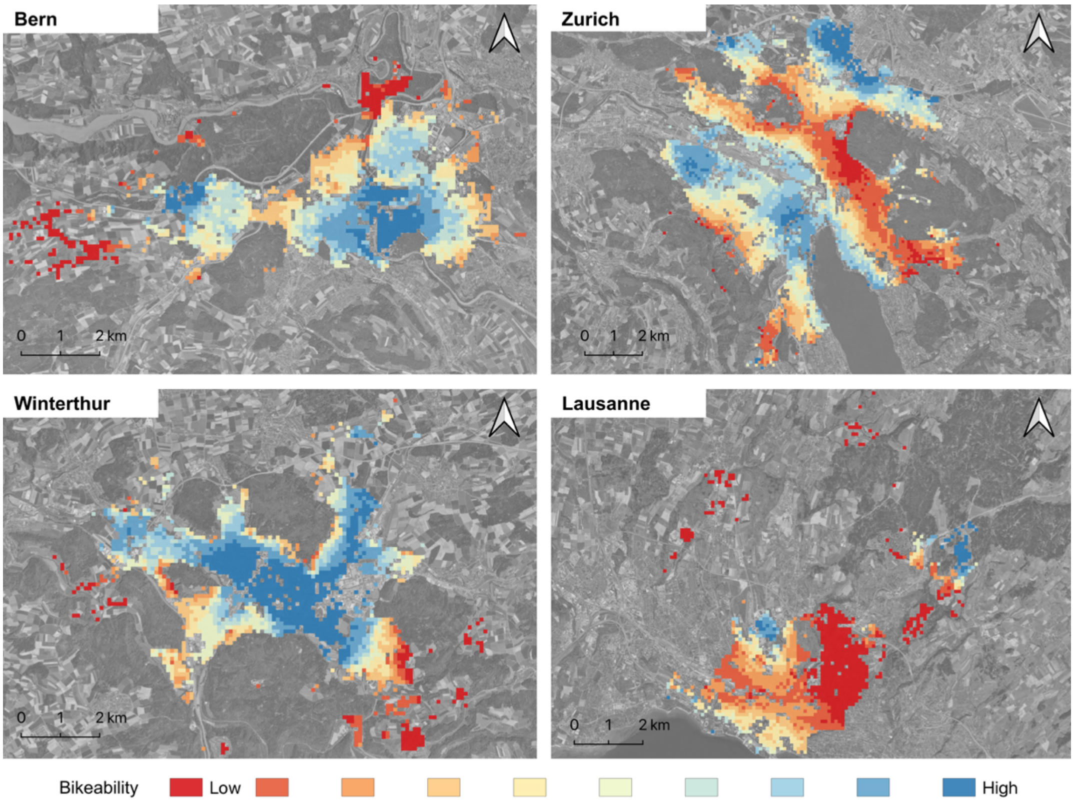

Figure 32 Index deciles for bikeability to leisure and sports facilities.

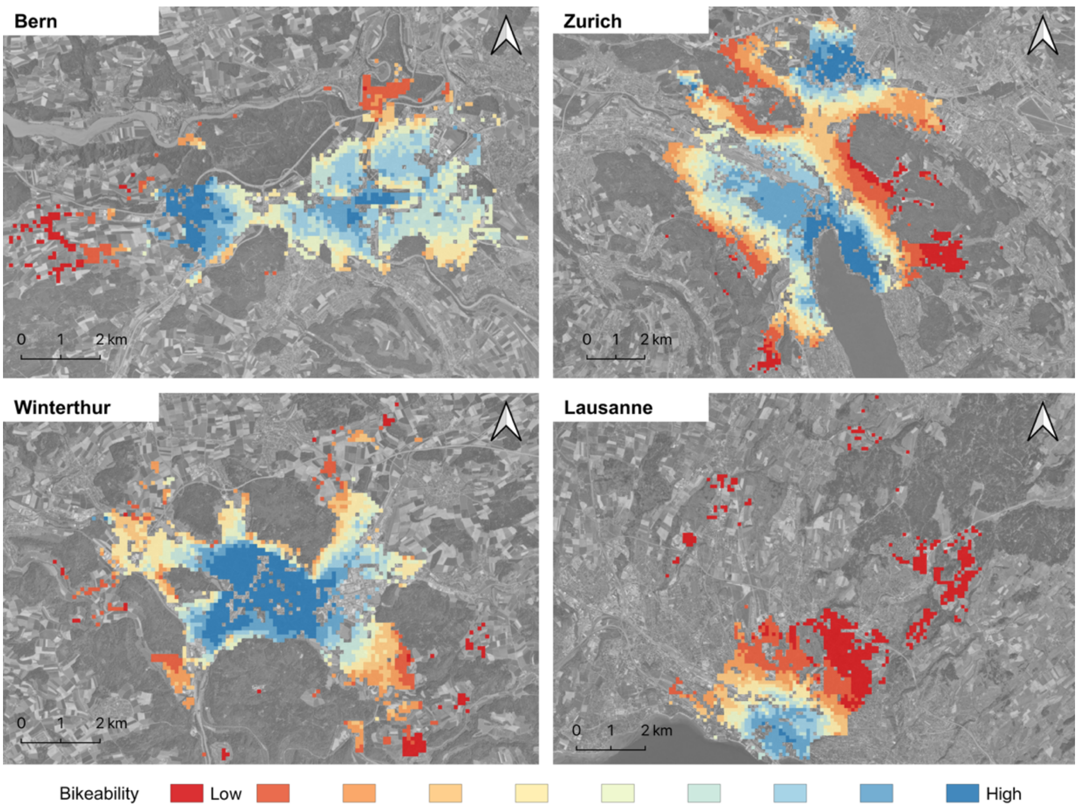

Figure 33 Index deciles for bikeability to public parks.

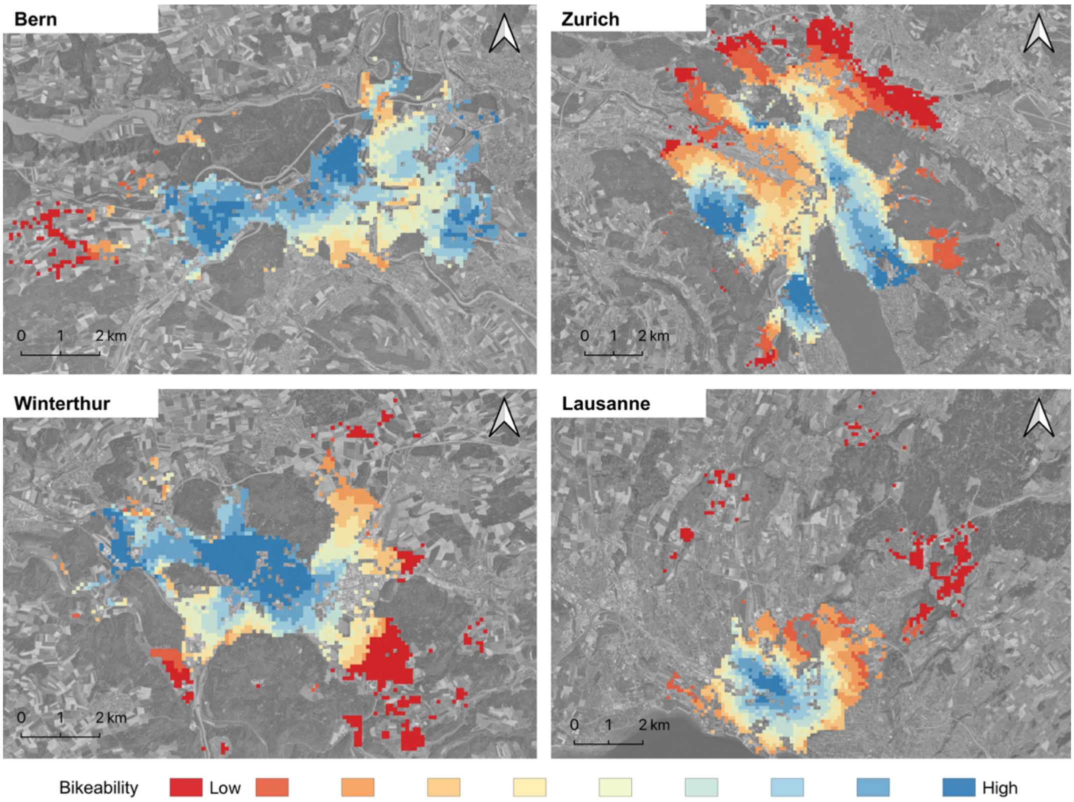

Figure 34 Index deciles for bikeability to hospitals.

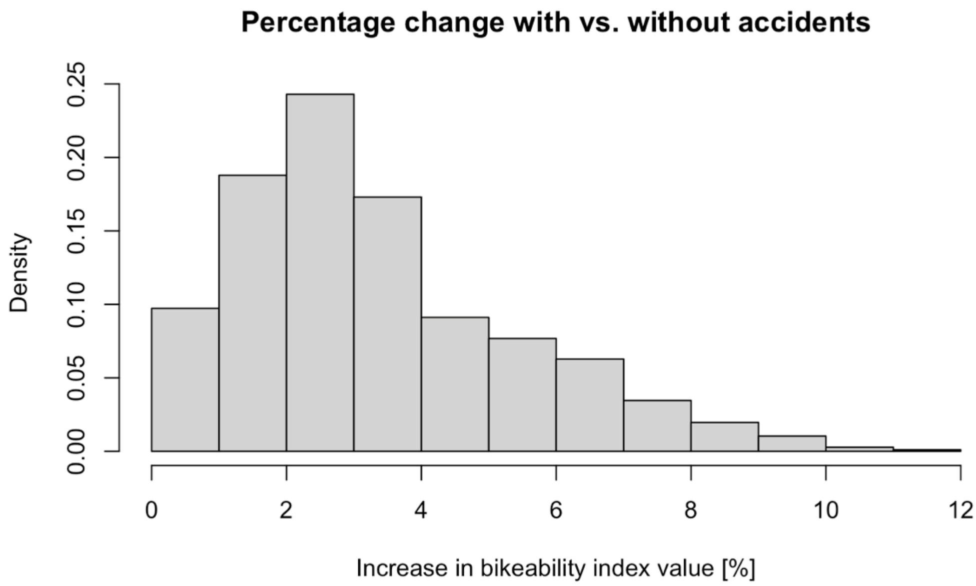

Figure 35 Histogram of the increase in bikeability index values additionally considering the number of bike accidents per network segment compared to the total bikeability index.

Figure 36 Violin plots of the bikeability index values for the four case study areas additionally accounting for the number of bike accidents.

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.

Nicola Maiani, 30.01.2024