University of Zurich[UZH]

Low-Stress Connectivity and Accessibility; 'Leave no one behind' in the Bicycle Network in the City of Zurich

GEO 511 Master's Thesis

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Abstract

This thesis presents a comprehensive analysis of Zurich's bicycle network based on the imposed traffic stress for cyclists. An adapted level of traffic stress (LTS) classification was introduced to suit the local road circumstances and the available data. It classifies the bicycle network into four categories of differing imposed traffic stress levels (LTS 1-4), all relating to a respective cyclist group with the according LTS tolerance. The resulting classification reveals that apart from Zurich's forest areas, LTS groups 1 and 2, the most vulnerable cyclists with the lowest traffic stress tolerance, are presented with cut-up and mostly disconnected parts of the bicycle network. This work then proceeded to examine the connectivity and accessibility to public services of the respective suitable networks of LTS groups 1-4, further demonstrating the inadequate and lacking network for LTS groups 1 and 2.

While comparing the results of Zurich's bicycle network with the city's current and past plans and policies, this work explores the planned bicycle network of the 'Velostrategie 2030', Zurich's planning strategy to improve bicycle transportation in the city. Results show that while an ideal implementation of the planned *cycling fast routes* will improve the overall connectivity and accessibility of all groups, they are not sufficient for LTS groups 1 and 2, but significantly benefit LTS group 3, especially on longer trips. Further analysis of the proposed *base network* of the planned network shows its crucial importance for low-stress cycling connectivity and accessibility.

This thesis concludes with planning and policy recommendations, emphasizing the need for special attention to the low-stress cycling groups LTS 1 and 2, representing a big part of citizens currently presented with an inadequate cycling network for their traffic stress tolerances. With its wide range of results, this work offers valuable insight for planners and policy-makers to create a more inclusive and effective bicycle network in the city of Zurich, while simultaneously highlighting the importance of including local variables in the level of traffic stress methodology.

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1 Introduction

1.1 Background and Motivation

With the growing importance of environmentally friendly means of transportation and the connected need for future-oriented spatial planning, the bicycle is recognized as an essential component of urban traffic (Heinen et al., 2009; Meschik, 2012; Oskarbski et al., 2021). Nonetheless, the current circumstances for urban cyclists leave much to be desired in most cities worldwide. Usually manifested in the form of insufficient infrastructure, the bicycle often gets pushed aside by other, more prominent modes of transportation. The combination of the rise of successful implementations of bicycle-centered or at least bicycle-friendly urban planning strategies and the lifelong personal experience of cycling in a city centered around cars and public traffic has inspired this thesis to dig deeper into the state of bicycle transportation in the city of Zurich. Although the city has been and is planning to further increase the significance of the bicycle as a valid mode of transportation in the future, the current situation led to Zurich being rated the worst Swiss city to cycle in 2021 out of 45 rated cities (Prix Velo, 2022).

Coupled with a notably slower growth of bicycle transportation in the modal split of transportation compared to other Swiss cities (BFS, 2023), this rating points to potential problems in Zurich's bicycle transportation system. In a city that is relatively dense by Swiss standards, these symptoms pose complex questions of space allocation from a planning perspective. However, they also raise questions about the users of the bicycle network and, more importantly, those who choose not to use it.

From personal experience, it is evident that certain demographics tend to use this mode of transportation extensively, while others are rarely seen. A problem that comes up regularly is that many people would not feel safe or confident enough on Zurich's roads. This inspired this thesis to also build on the principle of "Leave no one behind" to determine whether the current state of the bicycle network is a contributing reason for this lack of confidence and perceived safety. If it does, this study aims to assess whether the plans of the city are designed to make the bicycle network more inclusive and accessible for all citizens.

1.2 Research Objectives & Questions

A narrow bicycle lane abruptly ends, leading into a traffic light, where the cyclists can choose between evading onto the sidewalk to the right, the tram lane to the left, or staying behind the row of cars that were forced to drive right beside the sidewalk due to the narrow road. These three options, the first two notably being illegal but much faster, are being presented to cyclists in Zurich on a daily basis. A map of existing bicycle lanes and bicycle paths confirms that these situations are common in Zurich, resulting in regularly unconnected parts of bicycle infrastructure. Cyclists react differently to situations like these; some are reluctant and scared, others stressed but accepting, and others indifferent and relaxed because they have been in this situation hundreds of times.

Urban planning, as a principle, is supposed to equitably and fairly distribute a city's space between all actors involved in it (Gössling et al., 2016). In our example of the cyclist waiting at the traffic light, the space distribution conflict with other modes of transportation like cars or public traffic is relatively apparent. Two different cyclists, however, are as much two different actors in traffic as a cyclist and a car driver are. As the usually weakest mode of transportation on the road, the perception differences between cyclists can differ significantly from situation to situation.

These differences are often a perceived lack of safety and can stem from a range of reasons, from general ability to ride a bicycle, age, gender, fitness, or a combination of these and more (Winters et al., 2008). The inclusion of this diversity of cyclists is not a new concept in urban planning. It has also been incorporated in the bicycle planning strategies of the city of Zurich (2021). However, a specific way of assessing and quantifying these perceptions and their connected problems seems to be missing.

This work aims to fill that gap by determining how the current bicycle transportation situation is suited for different types of cyclists. An emphasis will be laid on the connectivity and accessibility of the bicycle network, recognizing how important they are for cyclists, like for any transportation mode (Mekuria et al., 2012). The objective of the thesis is to create a tool that can be used to not only spatially assess the current situation of different groups of cyclists but also to evaluate the city's efforts regarding the different experiences of these groups. With these goals in mind, this thesis tries to answer the following specific research questions:

- RQ1: Are specific groups of citizens excluded from bicycle transportation in the city of Zurich due to a lack of connectivity and accessibility in the bicycle network based on their level of traffic stress tolerance?

- RQ2: How do the future efforts of the city to improve bicycle transportation affect network connectivity and accessibility, and are they equitable for all types of cyclists?

1.3 Scope and Delimitations

This thesis aims to build on existing literature and their methodologies, which will be described later in the section 'Literature Review'. As the traffic situation is different in the city of Zurich as it is in the mostly North American cities the existing literature is based on, this work will include important aspects and variables specific to Zurich. This implies that certain aspects will be customized to suit Zurich's specific context, which in turn produces a tool that will be less suitable for generalized application in other cities but more precise and realistic for this use case. To combat this notion, which will be discussed more in-depth in the section 'Methodology', it tries to be flexible in its function inputs to increase transferability to other case studies.

The size of the study area is relatively big and therefore, is planned to shed light on spatial differences within the city but will increase the potential for errors due to its size. This means that the results should not be taken at face value but are rather suited to give an overview of the situation of the city while pinpointing potential problems that can be observed from comparing the different results. The section 'Methodology' and the subsection 'Limitations' will further discuss this point.

1.4 Thesis Outline

In the next section 'Literature Review', this thesis will dive deeper into research that has been done on bicycle transportation planning as a whole. More specifically, the importance of bicycle networks will be analysed, and the particular network approach used in this thesis will be described. Along the way, research gaps will be identified. After a shorter section about the study area and the data, the section 'Methodology' will describe the methods used in more depth. Following the same structure as the Jupyter Notebook that will be created as the tool of this thesis, the methodology section touches on data processing, the primary methods, the following network analyses, and the exploration of the planned future network of the city. Further, the section 'Results' will explore the outputs of the Jupyter Notebook. The following section 'Discussion' will first discuss the results in the context of the existing literature and second will critically evaluate the implications of the modeled planned network and the derived planning and policy recommendation for the city. Third, it states the limitations of this work. The thesis will end with a conclusion, including potential future work.

2 Literature Review

2.1 Bicycle Transportation Planning

Over the course of the past few decades, the bicycle has risen from being a neglected form of transportation to becoming a cornerstone of urban mobility (Pucher and Buehler, 2017). This rise can be attributed to a combination of different factors. First, it is one the most environmentally friendly modes of transportation, which is crucial in the age of drastically rising CO^2 levels, with the urban transportation sector being a growing contributor (Hickman and Banister, 2014). Second, it is a very efficient mode of transportation regarding the use of space, which can help alleviate rising congestion problems in cities (Hamilton and Wichman, 2018). Third, bicycle transportation is a very equitable mode of transportation compared to motorised individual traffic and public traffic as there are little to no connected costs to it (Buehler and Pucher, 2021). Last but certainly not least, it promotes physical exercise for users (Garrard et al., 2012), which has direct health benefits (Mueller et al., 2018; De Geus et al., 2008) and therefore also helps to combat the worldwide rising obesity rates, which pose problems not only on people's personal health but also on health care systems around the world (Organization et al., 2022).

Despite these benefits, bicycle transportation planning has long been marginalised in urban transportation planning and is just starting to pick up in popularity in recent years (Koglin and Rye, 2014; Pucher and Buehler, 2017). One reason for that is, as already discussed in a paper from 1976, that the bicycle was only seen as being used for recreational purposes instead of serving as a viable means of urban transportation (Hanson and Hanson, 1976). Additionally, there was little to no data and a lack of role models of cities to show planners and officials that people would start cycling if the appropriate infrastructure were to be built (Hanson and Hanson, 1976). Finally, the lack of interest in bicycle transportation planning was also closely related to the boom of cars after the Second World War (Oldenziel and Bruhèze, 2011). The economic and cultural post-war success story of the car not only forced urban planning to align itself to serve the needs of cars in the city but, in reverse also incentivised the further success of the car. This in turn meant that the bicycle was neglected and sometimes even erased from urban planning and policies (Oldenziel and Bruhèze, 2011), from which, in some places, it is still recovering from today. Interestingly and often forgotten, before the Second World War and the concurrent rise of cars, the bicycle played a much more central role in cities due to similar reasons as stated above. The cheap and practical bicycle was used extensively for not only recreational purposes but also as a valid mode of transportation to get to work or even to deliver goods (Oosterhuis, 2016).

Bicycle transportation planning involves different disciplines and actors and can apply a multitude of different strategies to promote cycling as a valid mode of transportation. Like other transportation planning fields, different strategies operate on different scales, ranging from a few meters of roads up to overarching networks of whole cities or even countries. However, infrastructure development is most often the underlying strategy employed, regardless of scale (Dill, 2009). This is due to a simple fact that has been shown and replicated in different cities, mostly in countries like Sweden, Germany, or Denmark (Pucher and Buehler, 2008). That is, good bicycle infrastructure incentivises people to use the bicycle as an everyday mode of transportation more than anything else (Pucher and Buehler, 2008).

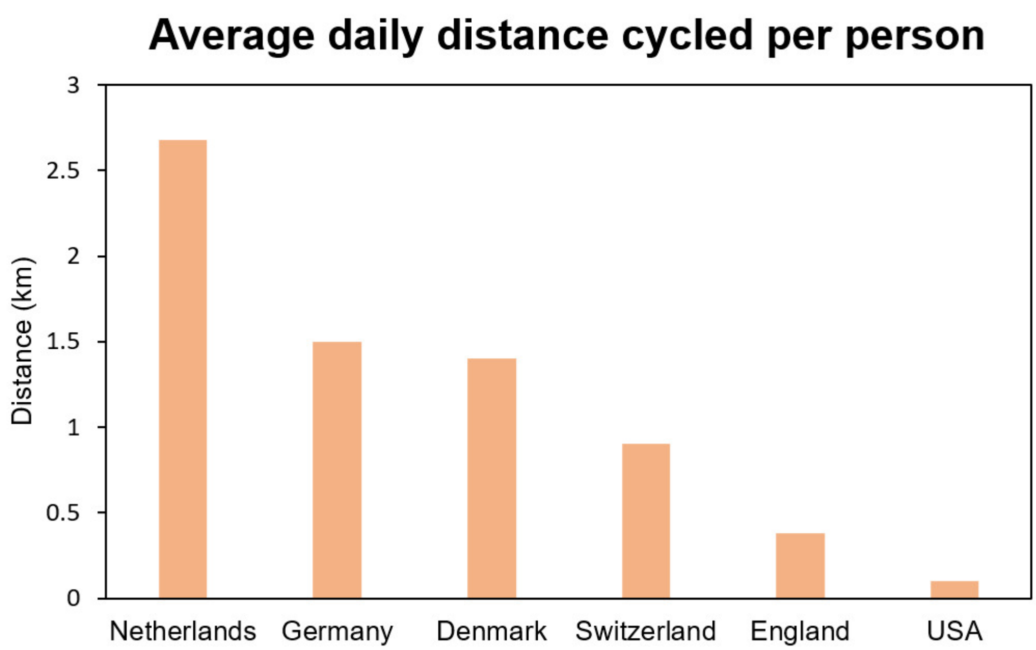

Figure 2.1: Average distance cycled per day per person, comparison of different countries. Source: https://discerningcyclist.com/bicycle-usage-statistics-by-country/ & Stadt Zürich (2021)

However, the planning of the suitable infrastructure for a particular situation is influenced by many different factors. Existing policies and regulations, missing funding, missing public support (Robartes et al., 2021) or the lack of space in urban areas usually define what can be realistically implemented. Even if a certain project is implemented in the best way possible, and like in every transportation system, there is a need for a usable overarching network of infrastructure in the city (Szell et al., 2022; Lowry and Loh, 2017). In the following subsections, this thesis will dive deeper into what design principles are required for a successful bicycle network and will explore different network approaches.

2.2 Bicycle Network Design Principles

The national platform for transport, infrastructure and public space of the Netherlands (CROW) released the "Dutch Design Manual for Bicycle Traffic" in 2007, which has been used and adopted since then in a multitude of different bicycle traffic studies (Mekuria et al., 2012; Winters et al., 2016; Wysling, 2021). It proposes a framework of five design principles for bicycle networks: *safety, directness, comfort, cohesion, and attractiveness* (CROW, 2007). These five design principles can be roughly divided into two categories. The perceived *safety, comfort* and *attractiveness* of cyclists can mainly be derived from the attributes of the cycled road or path and their surroundings. It includes various attributes from more obvious variables like bicycle infrastructure, speed limit, traffic flow, road geometry, and the presence of car parking spots up to subtler variables like road surface, curb geometry, signalisation, or nearby vegetation (Mekuria et al., 2012; Kang and Lee, 2012; Reggiani et al., 2022).

Safety or the lack thereof is known to be one of the most relevant factors for whether people feel comfortable cycling in a city (Cleland and Walton, 2004). A multitude of studies have attempted to quantify bicycle safety but faced similar challenges, often regarding accident data. Bicycle accident data is often incomplete due to missing reporting of minor accidents or hard to analyse because the amount of bicycle trips without accidents is unknown (De Geus et al., 2008; Martin et al., 2016). However, by improving bicycle infrastructure (DiGioia et al., 2017), reducing speed limits (Isaksson-Hellman and Töreki, 2019), or removing parallel parking spots (Schimek, 2018), cyclist safety can be drastically improved. Additionally, a phenomenon called safety-in-numbers has been studied and deemed to be true for upcoming bicycle cities, which implies that with greater numbers of cycling people, car drivers are more aware of them, which results in lower amounts of accident between them (Tin et al., 2011; Jacobsen, 2015). The design principle *comfort* defines itself more through that the experience of cycling should be pleasurable and straightforward, whereas *attractiveness* goes as far as making the experience beautiful and inviting so that it attracts people that would not cycle otherwise (CROW, 2007). Although there are a few intricacies between them, this work will not get into them too specifically, as they are influenced by mostly the same variables as the other design principles, which will be analysed in more depth.

The remaining two design principles *directness* and *cohesion* focus on the quality of the bicycle network from a more holistic view. As the name implies, a direct bicycle network is supposed to have minimal detours, should be as effortless to ride as possible and according to CROW (2007), should at least be as direct if not more direct than the road network for cars. The cohesion of a network is an elementary requirement of any mode of transportation. It signifies whether it is possible to get from point A to point B of the network (CROW, 2007). This includes trips of different lengths and intentions. A combination of both directness and cohesion can be found in the two following, more specific measures that can be derived from a network, connectivity and accessibility.

2.2.1 Connectivity

Network connectivity is a relevant, if not crucial measure of how usable a network in reality is (Mekuria et al., 2012; Winters et al., 2016; Koohsari et al., 2014). Like cohesion, it describes how connected different points in the network are and the ease of their connection (Boisjoly et al., 2020). However, in contrast to directness, which acts more as a prerequisite of connection, network connectivity determines the level or quality of the connections and can be assessed through different kinds of measures. For instance, connectivity can be measured by structural components of the network like intersection density (Lowry et al., 2012), but also by more cyclist-centric methods, which include their perception of the network in regards to safety and stress (Lowry and Loh, 2017; Mekuria et al., 2012). More specific calculation methods of connectivity will be discussed in an upcoming chapter focussing on bicycle network modeling approaches.

Although the concept of connectivity is undisputed, there is not one clear definition of it. In some research, it is generalised as the physical connections that allow cyclists to move from one place to another. In contrast, in Lowry and Loh's work (2017), it is defined as the ability to reach specific essential points of interest. This second definition is more often regarded as network accessibility, which is also a prominent aspect of bicycle network planning.

2.2.2 Accessibility

Accessibility can be defined as the ability to reach a desired destination (Kent and Karner, 2018; Gehrke et al., 2020). In the transportation planning sector, this refers to the network associated with the specific mode of transportation in question. Depending on the question the accessibility analysis is trying to answer, different origins and destinations can be chosen. So-called origin-destination pairs (O-D pairs) can be chosen at random out of defined origins and destinations (Kent and Karner, 2018) or can be very specific, e.g., accessibility to this particular destination (Wang et al., 2018).

Traditionally for transportation planning, and therefore predominantly for motorised traffic, accessibility has been explored on the axes of time and distance (Kent and Karner, 2018). Simply put, given a georeferenced network and the speed of the mode of transportation in question, an assessment can be made about which nodes and segments are accessible from a specific origin and which are not (Geurs and Van Wee, 2004). However, distance and time are far from the only axes that can be explored with accessibility analyses. A network model, which is ultimately one of its biggest strengths, allows any weights for its nodes and edges. For an accessibility analysis of a car network, this can for example be calculating realistic speeds of travel through the network with either more straightforward calculations by including speed limits and traffic lights (Salonen and Toivonen, 2013) or through more complex calculations with dynamic weights that change in real-time (Szeto and Wong, 2012).

Network models for both motorised individual traffic and public transportation often only focus on speed, efficiency, and the shortest path to the desired destination (Nha et al., 2012). This is however insufficient and too simplistic for bicycle transportation. Due to the fact, that bicycles are as vulnerable as they are, speed and efficiency are not only less important than for other modes of transportation but also less important compared to other interests of bicycle users (Kang and Lee, 2012). Based on this vulnerability, the strength of network models for bicycles lies in the fact that they can merge different design principles. The edges and nodes provide information about cohesion and directness and can also be weighted according to variables and inputs, which are proxies for safety, comfort, and attractiveness. The following chapter explores an approach that tries to integrate all these design principles into a network model: the concept of the bicycle level of traffic stress.

2.3 Bicycle Level of Traffic Stress (LTS)

There are different ways of defining a bicycle network. The most obvious would be the sum of all roads and paths in a city where it is permitted to ride a bicycle and where a planner would expect bicycles. A second definition would be what Mekuria et al.(2012) would call an inventory definition and is just the road and intersections where the responsible authority decided to put any kind of bicycle infrastructure or signalisation. However, both those definitions deviate from reality for the same reason. Just because there is no signal or bicycle infrastructure on a small neighbourhood road, a cyclist would not normally choose not to ride there if they feel comfortable. In turn, the same cyclist might feel uncomfortable riding on a bicycle lane on a big road and therefore avoid it, although it is technically part of the bicycle network (Mekuria et al., 2012; Lowry et al., 2016). The bicycle of level traffic stress (LTS) fills this gap by introducing a more user-oriented way of assessing whether a person would ride or rather avoid certain road segments and intersections (Mekuria et al., 2012; Winters et al., 2008).

2.3.1 LTS Groups

Bicycle level of traffic stress builds on the fact that cyclists have varying amounts of stress tolerance while cycling (Mekuria et al., 2012; Dill and McNeil, 2013). This traffic stress is influenced by many factors such as speed limit, daily motorised traffic flow, bicycle infrastructure, and more (Mekuria et al., 2012; Lowry et al., 2016). In a bicycle user classification scheme developed by Geller (2009), there are four types of cyclists. The group 'Strong and Fearless' would ride a bicycle under any circumstances and corresponds to 4-7% of the population (Dill and McNeil, 2013, 2016). The second group, 'Enthused and Confident' with around a 5-9% share, are cyclists that are comfortable with most of the common situations like sharing a busy road with motorised traffic, however only with an acceptable speed limit and bicycle infrastructure (Geller, 2009; Dill and McNeil, 2016). The third group, 'Interested but Concerned' is the biggest group of cyclists with 51-56%, who mostly like riding bicycles but often do not use them as an active mode of transportation because they do not feel comfortable or safe enough riding in some situations. Finally, there is the group of 'No way, no how' (31-37%), which is not interested in cycling, either due to being extremely uncomfortable cycling anywhere or due to a general disinterest in cycling (Geller, 2009; Dill and McNeil, 2016). As these categories were widely adopted and validated in bicycle transportation planning (Dill and McNeil, 2012; Félix et al., 2017), the bicycle level of traffic stress methodology adopted them in a way to simplify the vast differences in perceived traffic stress levels (Mekuria et al., 2012; Lowry et al., 2016).

The 'No way, no how' group is excluded from the level of traffic stress methodology because they are not the target group of the bicycle network, even if a small percentage of them would potentially start cycling if significant improvements were made to the bicycle network (Geller, 2009). The group 'Interested but Concerned' is however split into two groups due to different needs and perceived stress levels (Mekuria et al., 2012). The first group represents the main portion of adults in Geller's group, whereas the second group consists of the children, who need special attention due to factors like low speed, lack of control of the bicycle, or a limited ability to communicate with other road users (Mekuria et al., 2012). The discussion of a city that should be suitable for people aged 8 to 80 has grown in recent years, and therefore not only children but also seniors will be part of this last group, as they need an equivalently safe network due to their high age. This results in the four following LTS groups:

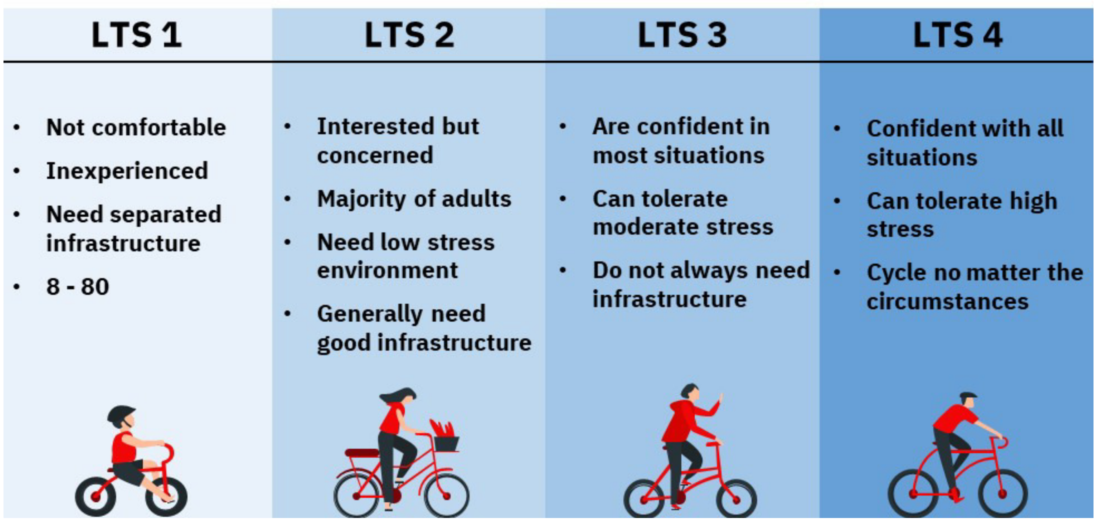

Figure 2.2: Level of traffic stress groups, vector graphics from slidesgo.com

This subdivision describes the main target groups of the respective stress levels and does not represent hard borders but rather a guideline. Inexperienced adult bicycle users might as well have the same stress tolerance as children and therefore fit the LTS 1 group, and some children can also have the stress tolerance of the LTS group 2 or 3.

2.3.2 LTS of Facilities

Related to these four LTS groups, a classification scheme of cycling facilities is defined, through which all network components are assigned a level of traffic stress corresponding to how much stress is imposed on cyclists. The existing bicycle infrastructure is the differentiator, separating the road segments into three main facility classes: Bicycle paths, which are physically separated from the road traffic, bicycle lanes on the road, and mixed traffic without any bicycle infrastructure (Montgomery County, 2017). Separated bicycle paths have been shown to be the safest and most comfortable bicycle infrastructure to ride on and therefore are adequate for the level of traffic stress group 1 (DiGioia et al., 2017). For the two other classes, additional variables are employed to define which road segment belongs to which of the four traffic stress levels. Street intersections are also ranked and assigned a traffic stress level depending on the signalisation of the intersection and additional infrastructure that provide easier and safer intersection crossings for cyclists like pocket bicycle lanes (Mekuria et al., 2012). To clarify, for the rest of this thesis, the abbreviation 'LTS n' can stand for either the result of the classification (road segment is tolerable for group n) or for the user group with stress tolerance n.

With the assignment of a bicycle traffic stress level of every road and intersection, a network is created for every LTS tolerance group consisting of the equal and the lower acceptable stress levels (e.g., LTS group 3: LTS 1-3) (Winters et al., 2016). These resulting four networks can then first be qualitatively analysed as they reveal patterns, for example 'islands' where cyclists of a certain LTS tolerance can move inside but are prohibited from moving outside due to an excessive amount of traffic stress (Mekuria et al., 2012; Winters et al., 2016). Second, they can be quantitatively analysed by calculating measures of connectivity and accessibility of each individual network to not only assess their individual quality but also to compare them to each other. The findings of the research that is done on bicycle level of traffic stress are in some cases just clusters of connectivity (Mekuria et al., 2012), in other cases proposals for potential infrastructure improvements (Winters et al., 2016) or general project or policy prioritisation and recommendations (Kent and Karner, 2018). While the results of the best-performing network improvements are often stated, the planning and policies are rarely discussed in regards to their equitability.

2.4 Low-Stress Connectivity & Accessibility

While the general connectivity and accessibility of a network give valuable information about its quality and practicability, low-stress connectivity and accessibility provide a more specific overview of the situation for the two LTS tolerance groups 1 and 2. These two groups can not only make up for up to 80% of the bicycle users (Dill and McNeil, 2016) but are also the groups that are the most vulnerable and therefore need good bicycle infrastructure and road conditions (Mekuria et al., 2012). The Dutch bicycle guidelines also target the equivalent of these user groups and have proven to have had significant success with up to 80% of the population using their bicycle weekly (Mekuria et al., 2012).

Within the four networks of the LTS groups, phenomena like islands of low-stress connectivity and high-stress barriers exist predominantly for groups LTS 1 and LTS 2, which not only significantly reduces the quantitative measure of connectivity but also the real-life usability of the network, as the furthest point one can travel to may just lay inside their small neighbourhood (Winters et al., 2016). Increased low-stress connectivity has been found to be positively correlated to the number of bicycle trips (Lowry and Loh, 2017), which shows that assessing and alleviating these symptoms of lacking low-stress connectivity is crucial for the bicycle as a valid mode of transportation.

Low-stress accessibility deals with the same difficulties as low-stress connectivity does, but does so more specifically by including more intention or more of a question formulation, for example specific start and end points (Kent and Karner, 2018). By including this question formulation, an additional axis of analysis is explored to the already present analysis of the four groups of differing levels of traffic stress tolerance. Low-stress accessibility analysis of spatial subdivisions, either administrative subdivisions like city districts or also social subdivisions like rich/poor neighbourhoods (Duroudier, 2014) provides not only information about the differences between the different LTS groups inside of the subdivisions but also spatial differences between the different subdivisions (Kent and Karner, 2018). Low-stress accessibility bridges a gap to more critical voices regarding transportation planning problems regarding equity of opportunity (Kent and Karner, 2018), which a lot of LTS literature is not mentioning. Spatial accessibility is shown to be significantly related to socio-economic inequality (Scheurer et al., 2017), further increasing its importance in regards to an equitable bicycle network that leaves no one behind.

2.5 Alternative Bicycle Network Methods

Bicycle level of traffic stress is one of many approaches, which include the perception of bicycle users in the assessment of the bicycle network. The bicycle level of service (BLOS), an adaptation from the similar level of service (LOS) of motorised traffic, ranks road segments and intersections by perceived comfort levels into seven categories A-F (Landis et al., 1997). However, the ranking is done by collecting the comfort levels of test subjects (Landis et al., 1997; Kang and Lee, 2012). By relating these perceived comfort levels to the features of the roads they were recorded on, an assessment of the impact of the road attributes is made to finally predict the comfort level of other roads (Kang and Lee, 2012). Although the bicycle level of service was and still is one of the most used bicycle network assessment methods, it has some limitations.

The biggest of them, especially in comparison to the level of traffic stress, is that cyclists are seen as one homogeneous group with the same interests and stress perception. Although the weights of the variables are calculated by the experiences of different cyclists, the weight is just an average, which will not be sufficient for all users (Asadi-Shekari et al., 2013). Additionally, the data used for a BLOS analysis is often extensive as it can include data about sight distance restrictions or the motorised level of service (Dixon, 1996), which is not always available. Furthermore, the model of a BLOS analysis is often a black box, as many different weighted variables are included, making it hard to assess the underlying problem of the road segment (Mekuria et al., 2012). The LTS classification schema in comparison strives to be simple and comprehensible, not only for planners but also for the public (Huertas et al., 2020).

Throughout the reviewed literature, various other terms are used for similar concepts as the bicycle level of traffic stress, such as bicycle suitability, which is defined as the perceived comfort and safety of a road segment (Lowry et al., 2012) or bikeability, which is defined as comfortable and safe access to essential destinations (Wysling, 2021) and therefore very similar to low-stress accessibility.

2.6 Bicycle Data

One of the challenges of bicycle network planning in general is the availability of required data (Koglin and Rye, 2014). Compared to motorised traffic and public traffic network data, bicycle networks often need to be constructed from different data sets. Some data might include exact geometries of bicycle routes or paths, while others may lay somewhere on the side of or in the middle of a road. Combined with the fact that a lot of the additional variables are based on the road network and therefore have a different 'ground network', bicycle networks often need to be stitched together out of different data sets with different geometries, which ultimately is a source of errors while matching (Wysling, 2021). Although the LTS method requires more widely available data than other methods, it is still hard to transfer the classification schemes to other cities because it fails to address the differences and intricacies in road circumstances.

Bicycle safety data is another challenge of bicycle network planning. Bicycle accident data is the most direct indicator of bicycle safety, but it is hard to interpret due to different reasons (Biland, 2023). First, many bicycle accidents are not reported and therefore not included in the data. Second, there is very rarely data available on the total amount of bicycle users on the accident road, which would be necessary to evaluate the safety hazard of that road properly. Finally, the cause of the accident is hard to assign and often a combination of different factors. At the same time of writing this thesis, an analysis of bicycle accidents in Zurich regarding temporal patterns and the influence of network infrastructure is carried out in a different master thesis of the University of Zurich (Biland, 2023).

2.7 Bicycle Literature in Zurich

There is a sizeable amount of literature concerning bicycle transportation in Zurich. A big part of that is centered around shared micro-mobility (Reck et al., 2020, 2021) and route choice models (Menghini et al., 2010). A similar set of variables of this methodology was used in Menghini et al.'s (2010) work for modeling route choice of cyclists in the city of Zurich. Although some variables, like the existence of bicycle infrastructure, influence the perceived level of traffic stress, the work fails to include the variations of different types of cyclists. It also does not include some road situations specific to Zurich, which influence the stress level of cyclists. Two examples of that are tram tracks and pedestrian islands, both a proven safety hazard in the city. Notably, the work from Menghini et al. (2010) also proposed gradient as an important variable for route choice, which has been mentioned but often not included by bicycle level of traffic stress literature (Mekuria et al., 2012). As a means of making the case study as realistic as possible and also building on the experiences of existing bicycle literature of Zurich, this work aims to include all of these three variables.

2.8 Leave no one behind

One of the central promises of the sustainable development goals (SDGs) of the United Nations (UN) is to 'Leave no one behind', sometimes abbreviated as LNOB (UN, 2018). Although the concept is broad, it can be synthesised into the goal of ending poverty and reducing inequalities vertically and horizontally (Stuart and Samman, 2017). Besides its more obvious use in countries with extreme economic and social inequalities, the concept has found its way to various fields of studies to address more specific inequalities, for example in the digital world (Hernandez and Roberts, 2018) or in studies of gender and sexuality (Mills, 2015). The modern Western city is a place of a multitude of inequalities on many different scales and levels. On a big scale for example, they are responsible for a disproportionate amount of pollution and, consequently climate change, of which poorer countries tend to suffer from (Ganzleben and Kazmierczak, 2020). However, on a medium and small level, some are also closely connected to transportation planning and can finally be extended to bicycle networks.

Spatial inequality in a city can be seen as the uneven distribution of resources and services across a city. Many studies have shown that wealthier neighborhoods have higher access to what can be summarised as public services like healthcare facilities, schools, or supermarkets (Cortés, 2021; McKenzie, 2014). This accessibility to public services has long been known to be influenced and shaped by the spatial structure of a city and specific transportation networks, which are defined or at least influenced by the city's spatial and transportation planning (McLafferty, 1982).

As the instance that is at least to some degree in control of the transportation networks, urban transportation planning needs to make an effort in order to leave no one behind in the bicycle network. Stuart and Samman (2017, p.1) describe LNOB as the "recognition that the expectation of trickle-down is naive, and that explicit and pro-active attempts are needed to ensure populations at risk of being left behind are included from the start", which can be directly linked to the level of traffic stress groups 1 and 2, which need critical special attention and not just a general improvement of the bicycle network. A criticism that the Millennium Development Goals (MDGs), the predecessor of the SDGs, regularly received was that it focused too much on those who were easy to help, the lowest hanging fruits, instead of focussing on those who would need it most (Hernandez and Roberts, 2018). This notion of providing easy improvements for bicycle transportation can sometimes also be observed in bicycle transportation planning, albeit not in bad faith, and is a further reason of why 'Leave no one behind' is crucial to adhere to when working with bicycle networks.

2.9 Research Gaps

Although there is a vast amount of literature on the bicycle level of traffic stress methodology, to the knowledge of the author at this point in time, the following research gaps were identified:

1. The used criteria of the LTS classification are a mix of broadly available data and very specific data. Studies try to be as general as possible and therefore often fail to include different data baselines and local road situations.

2. Although there are studies of equity in bicycle networks, there are none that specifically include the concept of 'Leave no one behind'

3. There are no studies done on bicycle level of traffic stress in Zurich.

4. There are only a few studies that emulate the planned future network of a city and assess its effects on different LTS groups.

Based on the literature review, the available data, and the situation in Zurich, which will be discussed further in the next chapter, this thesis will try to fill these research gaps in the following respective ways:

1. The classification schema will be tailored specifically to Zurich. It will include the variable slope, which has been mentioned but rarely implemented in LTS literature (Mekuria et al., 2012), and additional variables specific to Zurich, like tram tracks and pedestrian islands.

2. The results, implications, and planned network will be directly compared to the concept 'Leave no one behind' and its general equitability.

3. It will give an overview of the bicycle LTS situation in Zurich, an emerging bicycle city that struggles to satisfy its bicycle users.

4. A future planned network will be analysed in the same manner as the current network. The results will be compared to each other to assess the potential of the planned network.

3 Study Area & Data

3.1 Study Area

Zurich is the biggest city in Switzerland with almost 450'000 citizens on an area of almost 92 km^2. While 24% of that area is forest and a further 6% are water bodies, there is a share of close to 14% of 'Verkehrsfläche', meaning space that is used by any kind of traffic (Stadt Zürich, 2023b). The forest areas are primarily hills or small mountains and therefore mainly used for recreational purposes. Besides the prominent lake, the 'Zürichsee', the river 'Limmat' splits the city into two parts, the bigger north-eastern side and the smaller but generally denser south-western side. Administratively, the city is divided into 12 'Kreise', which are similar to and therefore will be called districts, which are then further divided into 34 'Quartiere' which are smaller subdivisions, which in this work will be called neighbourhoods. A well-developed tram and bus network with over 430 stations is one of Zurich's main pillars of transportation.

3.1.1 Current Bicycle Situation

One of the key indicators for the assessment of the transportation behaviour of citizens is the modal share of transportation. The metric compares the use of the different modes of transport, either by the average amount of trips with the different modes per day, by the total amount of km traveled, or by time spent during those trips. Although all the different metrics of modal share have their validity, for example the total amount of traveled km can not give precise information about bicycle use as incomparably more distance is travelled with motorized traffic and public transport. The newest data on the modal share of Zurich is from a micro census of mobility and traffic, conducted every five years in Switzerland. In 2021, the modal share of bicycle trips in the city area only amounted to 8.6% of total trips, while 28.5% of trips were done by motorized individual traffic, 33.8% by public traffic and the remaining 29.1% by foot (BFS, 2023).

It is essential to realise that the Covid-19 pandemic still impacts the results from 2021 and therefore they have to be interpreted cautiously. The absolute transportation numbers for example have gone down for every mode of transport compared to the last survey in 2015, especially those for public transport, as citizens avoided it to practise social distancing. This additional public transport reduction can also be seen in the relative modal share in figure 3.1.

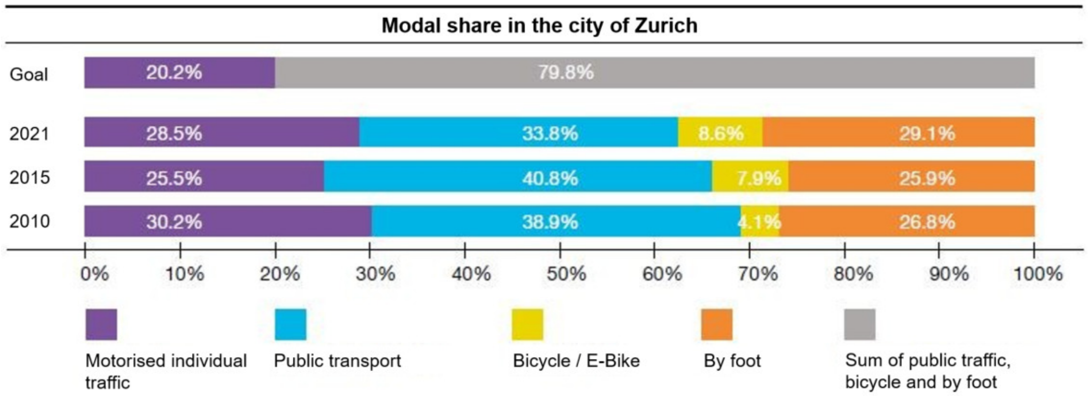

Figure 3.1: Modal share in the city of Zurich since 2010. Figure adapted from Nübold (2023). Note: The goal of the highest bar represents a goal of the 'Gemeindeordnung Zürich', described in the following section 'Plans & Policies'

While this reduction explains the percentage of public transport in the modal share, the rise in the bicycle share of just 0.7% is very minimal for what could have been during a time when people were actively trying to avoid public traffic. An analysis done by OUVEMA, the observatory of bicycles and active mobility, compares different Swiss cities regarding the modal share of trips of the city's citizens, however not only in the cities area. As seen in figure 3.2, Zurich is one of the two cities that even has a decrease in the modal share of cycling, while other big Swiss cities like Bern and Basel have experienced a significant increase since 2015 (Velojournal, 2023).

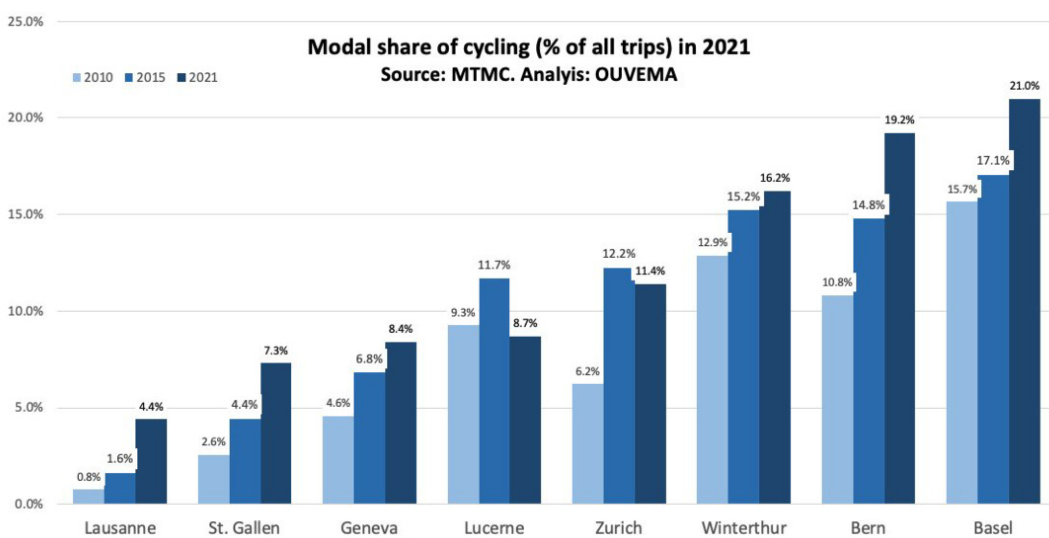

Figure 3.2: Bicycle modal share comparison of Swiss cities. Source: OUVEMA, micro census 2021

Although the modal share of the micro census paints a different picture, the amount of automatically recorded cycling citizens in the city of Zurich has been rising steadily and significantly over the past years with a growth of over 50% since the index year 2012 (Tiefbauamt Zürich, 2022). According to the civil engineering office, the pandemic impacted the development of bicycle transportation in Zurich and the results of the micro census deviated from the positive course it was on (Velojournal, 2023).

Even though the number of cyclists is a good indicator of the development of the bicycle transportation situation in Zurich, it does not include the citizen's perception of it. Prix Velo is an award given to Switzerland's most bicycle-friendly cities. It is based on a survey (n = 16'500) conducted every four years by 'Pro Velo Schweiz', an independent non-profit organisation that lobbies for improving the social, legal, and technical conditions for cycling. Although the number of participants out of Zurich was just above 1000 and therefore bared some uncertainty, Zurich was the worst rated city out of 45 rated cities in Switzerland with an overall insufficient grade of 3.4 on the typical Swiss grade scale (1 worst, 6 best, <4 insufficient). In the two categories safety and comfort, with grades 3.0 and 2.8, respectively, Zurich was ranked very insufficient (Prix Velo, 2022). This survey was predominantly filled out by members of Pro Velo and other bicycle-interested people, which might have skewed the overall picture somewhat negatively. However, a more representative survey that is conducted every two years from the Zurich's office for statistics, shows a similar discontent with the situation of bicycle transportation in Zurich. The satisfaction of the traffic situation as a bicycle user has steadily decreased in the last years, with almost 50% of surveyed citizens describing it as insufficient in 2021 (Statistik Stadt Zürich, 2022).

3.1.2 Plans & Policies

At the heart of the bicycle transportation planning in Zurich is the 'Velostrategie 2030', which replaced its successor, the 'Masterplan Velo' in 2021. It is an extensive strategy of the city with its main goals and measures until 2030, based on the goals and commitments of the 'Gemeindeordnung Stadt Zürich', the communal legal basis of Zurich. Due to the scope of this thesis, only parts of both documents that relate to this work will be touched on. For simplicity, the German technical terms will be translated as accurately as possible but might differ slightly from their original meaning.

The 'Velostrategie 2030' differentiates cyclists into four groups 'everyday drivers', 'habitual drivers', 'occasional drivers', and 'non-drivers'. Although these groups do not directly relate to the four LTS groups, they should have significant overlaps due to their riding habits. The 'everyday drivers' and the 'habitual drivers', who ride their bicycles 1-6 times a week, will mainly consist out of the two groups LTS 3 and LTS 4. On the other hand, the 'occasional drivers' and 'non-drivers' will mainly consist of the LTS groups 1 and 2. In comparison to Geller's (2009) 'No way, no how' group, the non-drivers of Zurich are decreasing every year and therefore show that at least a part of them are interested in cycling. As shown in figure 3.3, the 'Velostrategie 2030' groups generally relate to their size to the level of traffic stress groups. Cyclists who cycle rarely, the occasional drivers of Zurich's categorization, have shown to be more likely to feel unsafe and have a low traffic stress tolerance during their bicycle trips (de Jong and Fyhri, 2023).

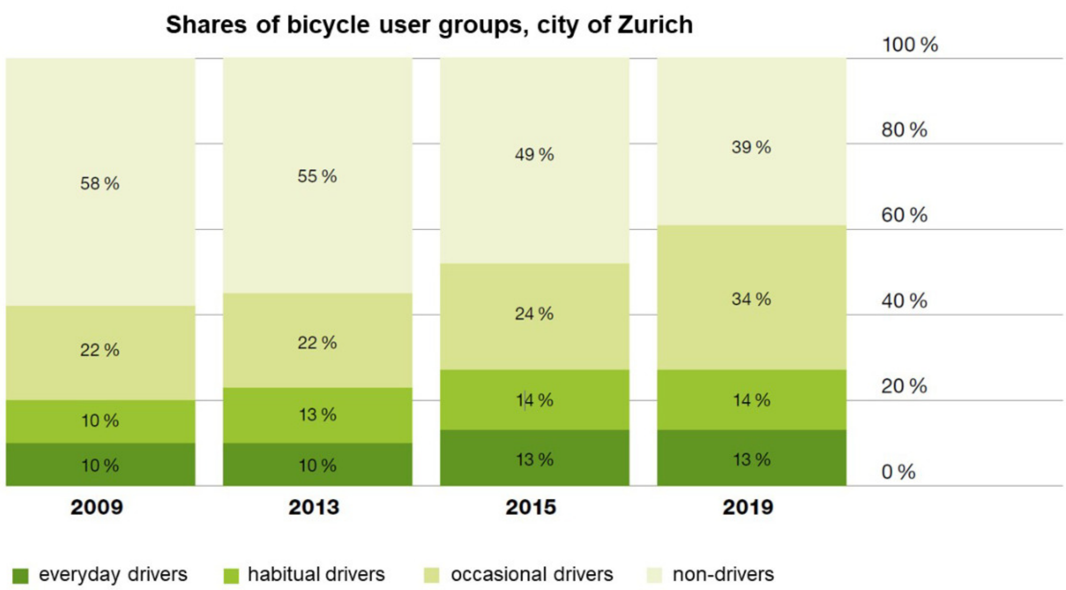

Figure 3.3: Shares of bicycle user groups in the city of Zurich. Figure adapted from the 'Velostrategie 2030' (Stadt Zürich, 2021)

One of the goals regarding these cyclist groups is

> "the creation of a direct, continuous and safe network, that is attractive for 'habitual drivers' and 'occasional drivers' to increase their share" (Stadt Zürich, 2021, p. 7).

More generally, the need for action until 2030 includes two points related to this work. First,

> "new focus will be put on a continuous, direct and visible bicycle and less on single routes" (Stadt Zürich, 2021, p. 9).

And second,

> "cycling should become attractive for the entire population. The prerequisite for that is a safe and simple network of cycle routes, especially for children, young people, and people who have barely used their bicycle so far" (Stadt Zürich, 2021, p. 9).

In the 'Gemeindeordnung', two specific paragraphs concern the realisation of bicycle traffic goals. The first one concerns the modal split of Zurich and says as follows:

> "The modal share of public transport, walking, and cycling in the total traffic volume in the city is to be increased by at least ten percent by October 24th, 2022; the decisive factor here is the distance travelled in the city area in relation to the total traffic." (Stadt Zürich, 2022, Art.154 Par.1).

However, in the ten years from the statement of this goal in 2012, the modal split of the modes of travel mentioned above just managed to rise by 1.7% of the stated 10% (Nübold, 2023). The second article regards a newer goal based on a public referendum that was accepted clearly (70.5%) in 2020:

> "The city implements a network of star-shaped as well as tangential fast cycling routes with a total length of at least fifty kilometers by no later than ten years after this provision comes into effect." (Stadt Zürich, 2022, Art.154 Par.3)

The fast routes in questions, also called 'Velovorzugsrouten' and with this name focusing not on speed but on the preference for cycling, are one of the three parts of a new network structure of the 'Velostrategie 2030', completed by a main network ('Hauptnetz') and a base network ('Basisnetz'). Although the city of Zurich prioritizes the term 'Velovorzugsrouten', for this work, they will be called fast routes for the lack of a better term and the similarity to cycling fast routes in other cities. These three parts of the planned network all have their different ascribed uses and therefore resulting target groups of cyclists. The role of the fast routes is planned to be the network element with the highest cycling quality regarding comfort, safety, and bicycle flow (Stadt Zürich, 2021). They aim to connect the different districts and neighbourhoods with direct and attractive cycling routes. To put them into perspective of the level of traffic stress groups, the fast routes are supposed to be suitable for the LTS group 1. Although they might not always be entirely separated from motorized traffic, high standards for infrastructure and continuous priority of passage are planned to make the routes suitable for citizens of all ages and cycling skill levels. The second level of the cycling network is the main network, which provides the most direct routes to essential destinations in the city. These routes do not have a standard of safety or comfort and will mainly be on bigger roads, mostly suiting only the level of traffic stress groups 3 and 4. The last part of the network, the base network, forms the smallest level of connections. It entails the fine-grained extension of the two other networks and allows cyclists to reach any destination (Stadt Zürich, 2021). They play an important part in the network not only for the LTS groups 3 and 4 but also for groups 1 and 2, as the fast routes would often not lead them to their desired destination. According to the application of traffic stress logic on this network structure, the would have to be suitable for the level of traffic stress group 1. Although they do consist mainly of low-stress residential roads, which can be suitable for the level of traffic stress 1, through the lens of the LTS methodology, a problem lies within the planning approach of the city.

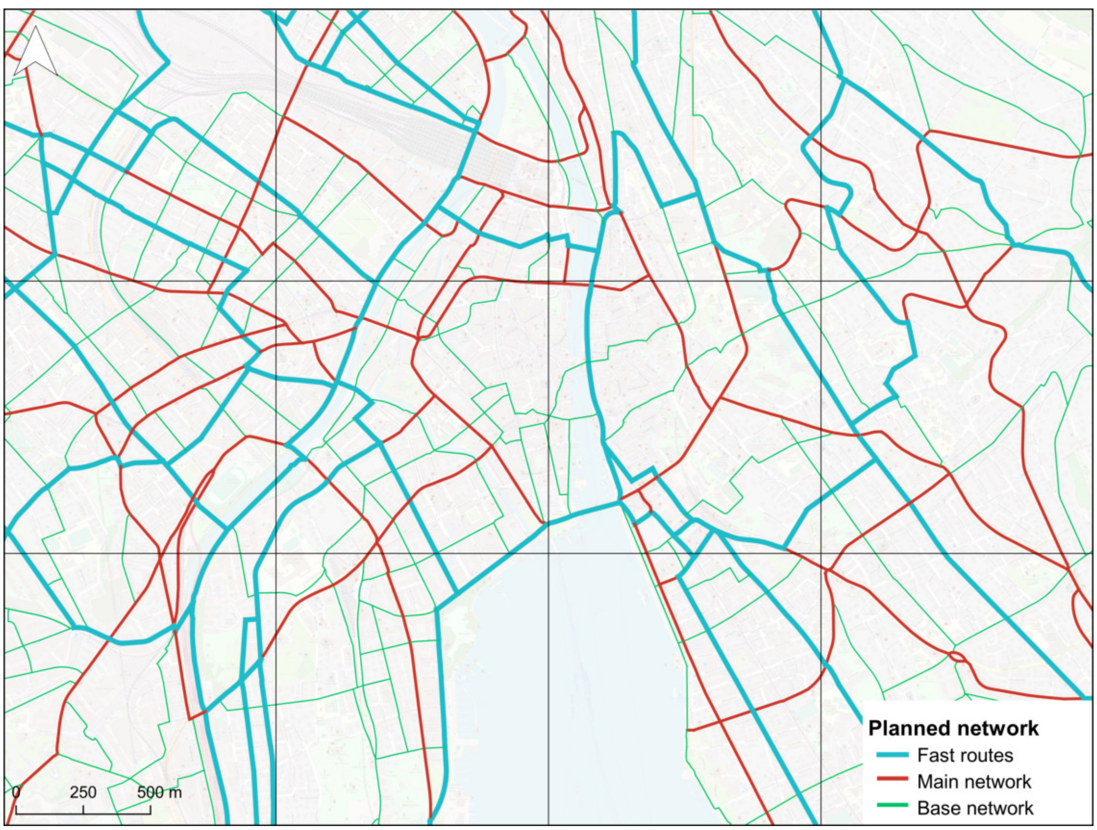

Figure 3.4: Planned network per categories, city center Zurich

According to the civil engineering office, the only part of this network that is being actively planned and constructed until 2030 are the fast routes. At least until then, the other two networks are only a passive part of the network. Passive planning in that context describes as much as, if any different projects are done on those routes (or any part of the city for that matter), the current bicycle situation will be analysed and improved if possible. However, no new projects will be introduced based on, for example a lack of safety on those roads. This planning approach seems especially concerning for the LTS groups 1 and 2, where the base network is essential to their overall connectivity and accessibility.

Although the 'Velostrategie 2030' and the fast cycling routes have earned much positive feedback, until 2021, Zurich's citizens were increasingly unhappy with the city's efforts for bicycle traffic. The question of how they rate the scope of measures to promote cycling was answered with too low or much too low with 50.8% in 2021, similar to the years 2015 and 2019 with 49.6% and 50.8% respectively (Statistik Stadt Zürich, 2021). These circumstances raise questions about the current state of bicycle transportation in Zurich and increase pressure on responsible transportation planners and the success of the planned projects.

3.2 Data

3.2.1 Sources

Table 3.1: Overview data sources

Use	**Parent data set**	**Attributes used**	**Source**
Bicycle ground network	Fuss- und Velowegnetzwerk	- Geometry - Bicycle infrastructure - Directions	City of Zurich
Road attributes	SwissTLM3D	- Road width	Federal office of topography (Swisstopo)
Daily motorized traffic	Verkehrsmodell 2018	- ADT	Civil engineering office Zurich (Tiefbauamt)
Speed limits	Signalisierte Geschwindigkeiten	- Speed limit	City of Zurich
Car parkings	Öffentlich zugängliche Strassenparkplätze	- Geometry	City of Zurich
Slope calculation	Digitales Terrainmodell 2014 (TIN)	- Z-values	City of Zurich
Pedestrian islands	Amtliche Vermessung	- Geometry	Federal office of spatial development (ARE)
Tram tracks	Linien des öffentlichen Verkehrs	- Geometry	Public transport Zurich (VBZ)
Planned network	Velonetzplanung	- Network lassification	City of Zurich
Points of interest	OSM POIs	- Geometry - POI type	OpenStreetMap
Accessibility origins	Amtliche Vermessung	- Building geometry	Federal office of spatial development (ARE)
Administrative borders	Statistische Quartiere	- Districts/Neighbourhoods	City of Zurich

The main data source for the level of traffic stress analysis was the city of Zurich, which has an open data portal with over 750 data sets with almost 100 data sets concerning mobility (OGD Zürich, 2023). Its pedestrian and bicycle network data set served as a foundation for the network for two reasons. Firstly, it included specific smaller segments and paths for bicycles, which sometimes act as important network components, for example a passage over a big busy road. Secondly, the rest of the network geometries were relatively simple and consistent, e.g., no duplicates or unconnected parts. For the level of traffic stress methodology, many additional variables had to be collected from different data sets. Besides the city of Zurich, the federal office of spatial development (ARE) was the source of the federal cadastral survey, while the federal office of topography (Swisstopo) supplied the SwissTLM3D, the national vectorized topographic landscape model. The two last sources for the attribute enrichment were the civil engineering office Zurich (Tiefbauamt Zürich) and the official public transport Zurich (VBZ). Therefore, all the data used for the network is from either the city of Zurich itself or a federal or municipal office, which means that certain broad assumptions can be made about their data quality. The data is supposed to be consistent and standardized, is supposed to be regularly updated, and should have a high degree of accuracy. Additionally, it should have high standards of documentation and strict regulations regarding privacy and security (Kitchin, 2015). The only unofficial data are the points of interest from OpenStreetMap, accessed through the Geofabrik service on 12.01.2023.

3.2.2 Assessment & Challenges

Without going into all the details of every data set, the following general assessments can be made with a few exceptions, which will be explicitly discussed. All data was from recent years, except the traffic model from 2018. Most of them are updated regularly or even continuously. By themselves, they are consistent regarding attribute values and other aspects like connected and valid geometries. There were no unexpected values or NULL values, and unclear values could always be looked up through clear documentations. However, in between the different data sets, there were some differences in road geometries. To enrich the road segments with attributes, three data sets had to be matched to the ground network. Although the matching of the main bigger roads was mostly unproblematic, the matching of intersections came with some degree of uncertainty and error because they had a lot of small differing geometries that were hard to assign automatically.

The matching of bicycle data is known to be a challenge due to the slightly deviating routes and differing data qualities (Vierø et al., 2023). The methods and challenges of the spatial matching process of this work will be described in the next section, 'Methodology'. Through a small amount of qualitative testing and local knowledge, the accuracy and completeness of the data sets were mostly confirmed to be good. Unfortunately, one of the more critical variables, the existing bicycle infrastructure of the pedestrian and bicycle network data set, is not updated continuously. Although most of the infrastructure is recorded correctly, with the last update of the data in November 2022, there is some bigger, newer bicycle infrastructure missing in the data. An example of that is a long wide bicycle lane on the 'Sihlquai' or a vital bicycle path on the 'Seilergraben'. Due to almost 60 localised improvements for the bicycle in the city in 2023 alone (Stadt Zürich, 2023a), this work decided against adding them manually to the data.

Notably, there are some differences in data availability compared to some level of traffic analyses. The classification scheme of Mekuria et al. (2012), Winters et al. (2016), or Montgomery County (2017) requires the number of lanes and their composition, which does not seem to exist for the city of Zurich. As a comparable variable, road width from the SwissTLM3D was used, and the classification was altered accordingly. One variable with a strong influence on the classification class, 'mixed traffic with bicycle lane', is the width of the bicycle lane. However, it could be ignored for Zurich at this point in time based on the fact that the old standard bicycle lane in Zurich measured between 1.20m and 1.50m in width, which is both below the threshold of the classification schemes of 1.80m, where bicycle lanes are significantly lowering the traffic stress level (Winters et al., 2016). Although the new standard of bicycle lane width is now 1.80m in Zurich (Kanton Zürich, 2021), at the point of the last update of the data of bicycle infrastructure, very few or possibly no bicycle lane was 1.80m wide. The rest of the variables that were deemed essential for the classification were available. Some classification schemes included additional information like bicycle lane blockage or reach from curb (Winters et al., 2016), which are unavailable for Zurich. Additionally, data of intersection bicycle infrastructure was not available, leading to a compromise of the LTS classification process, further described in the following chapter 'Methodology'.

4 Methodology

4.1 Overview

This chapter will dive deeper into the methods used in this thesis. The process was split up into four phases, as illustrated in the flow chart below. Phase 1 concerned all pre-processing that needed to be done, which included data manipulation and mainly the different steps of enriching the ground network with the attributes of other data sets. Phase 2 was the level of traffic stress classification of the bicycle facilities based on the attributes of the road segments. Phase 3 was the implementation of the connectivity and accessibility measures, which additionally included a Monte-Carlo simulation of the connectivity measure to ensure the function's stability. The last phase concluded the methodology by calculating the implemented measures from phase 3 for all LTS groups. Furthermore, in phase 4, the city's planned network was run through phases 2 and 3 and compared to the results of the current situation. The code of this thesis can be found in the following Github repository: `https://github.com/timfaessler/master_thesis_code`

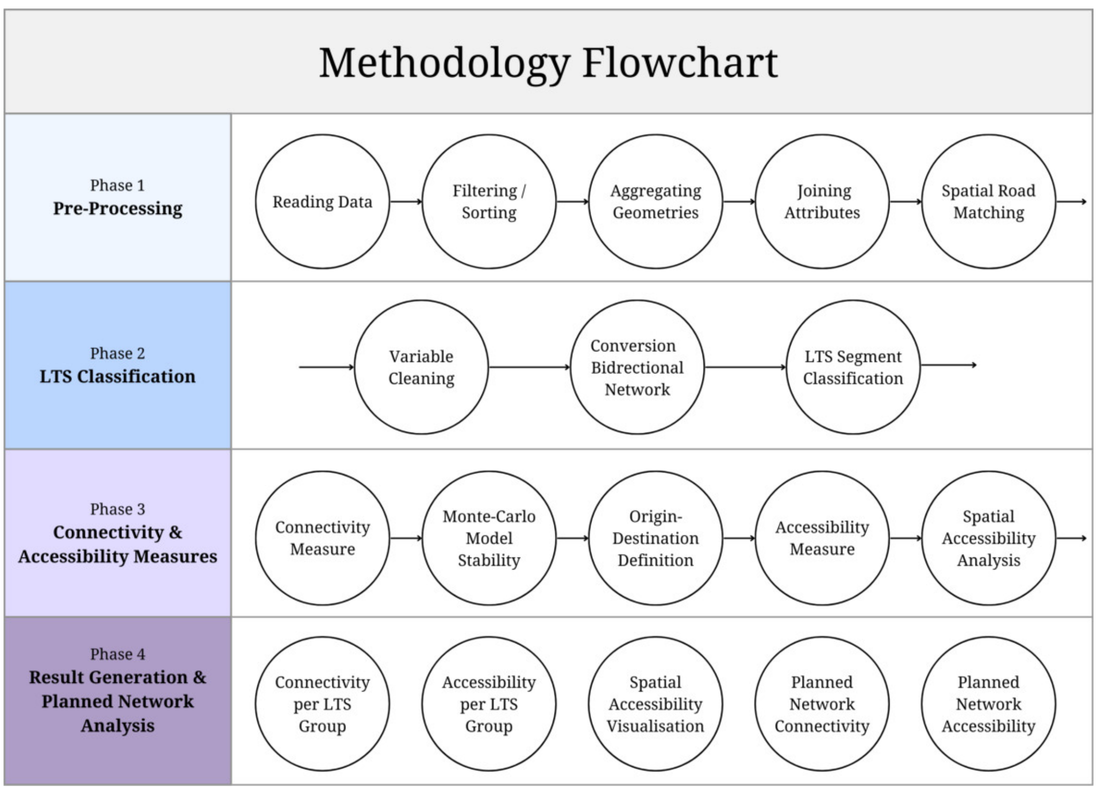

Figure 4.1: Thesis methodology flowchart

The implementation of the methods was carried out using a combination of Python and QGIS. A Python Jupyter Notebook was the central part with the same four phases as figure 4.1. The following goals were pursued in the coding of the Notebook: The Jupyter Notebook was designed to be as reusable as possible. However, because it included processing many specific variables and a need for pragmatism in certain sections, several parts were ultimately "hard coded". However, the essential functions like the LTS classification and the connectivity and accessibility measure were coded to be flexible to different inputs. Through an overall clear structure and concise descriptions of the functions and their inputs and outputs, the Jupyter Notebook (with the used data) should be usable as a tool for result generation without deep Python knowledge. Specifics of the implementation from a coding standpoint will be discussed as seen fit in the respective sections of the four phases. QGIS served as a tool for simplifying certain tasks and running some smaller functions, which would have unnecessarily clogged up the Jupyter Notebook. Additionally, it was used for visualising some results of the Jupyter Notebook. Various packages and libraries were used in the process, but the main two were GeoPandas (Jordahl et al., 2020) for spatial data manipulation and NetworkX (Hagberg et al., 2008) for network analyses. The NetworkX package served as a means for converting the road networks into network graphs while also providing essential path-finding algorithms.

4.2 Phase 1: Data Pre-processing

The goal of this section was to compile all the different data sources into one usable network ready for the level of traffic stress classification schemes. It therefore needed to fulfill the following requirements: The line geometries needed to meet the geometry requirements of a network graph, and roads needed to be enriched with all the attributes required for the LTS classification.

4.2.1 Network Geometries & The Weakest Link Principle

As mentioned before, the pedestrian and bicycle network data set of the city of Zurich served as this work's primary network geometries. As with any data set of this work, the coordinate reference system already matched the targeted one, the Swiss CH1903+/LV95, with the EPSG ID 2056. By simply filtering the geometries intended for bicycle use, the basic geometries of the network were extracted. To check and fix the geometric properties that are needed for a line data set to be valid for a network, three open-source functions were used inside of QGIS (Cadieux, 2022). Typical problems of invalid geometries for networks include disconnected edges, duplicate edges, or edge islands. Only a few problem areas were identified and able to be fixed.

After that, the first instance of the weakest link principle was applied to the ground network. The weakest link principle is a defining factor of the level of traffic stress methodology. It implies that the most negative part of a cyclist's experience is the defining factor of whether the user feels comfortable riding. This principle had implications on many different levels, as this work will show. This first one concerned the level of a network edge, meaning from one network node to another node. A network edge that, from here on out, also will be called a network segment can consist of multiple smaller parts with different attributes that each can have a defining impact on the whole road segment.

4.2.2 Simplification / Aggregation

The first application of the weakest link principle was the aggregation of these multiple smaller parts of the network segments so that every network edge only had one value per attribute. In the example of figure 4.2 on the left side, the upper left road consisted of one part with a bicycle lane and one part with no bicycle infrastructure.

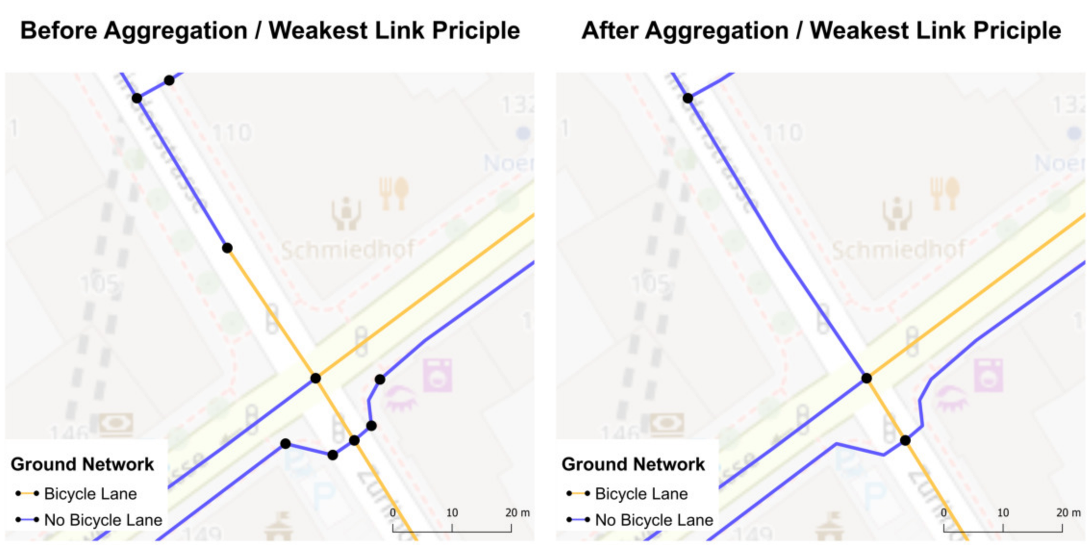

Figure 4.2: Comparison road segments before and after aggregation

For cyclists who are not comfortable riding on this road segment part without bicycle infrastructure, this whole road segment is not suitable. It was therefore aggregated as having no bicycle infrastructure at all. This aggregation logic not only applied to bicycle infrastructure but also to all other attributes. Logically, if two or more road segment parts were aggregated with the same attributes, the same attribute was transferred. In the Python code, this was solved by a suitable aggregation function from a forum, for which this work wrote some simple helper functions per variable, which decided which variable values needed to be prioritized or neglected depending on the weakest link principle. Depending on the values of the input variable, this included a series of if and elif statements for variables like bicycle lanes or just taking the highest value for attributes like the daily motorized traffic volume. This aggregation step was not only useful for applying the weakest link principle but also for eliminating unnecessary geometries and features, even if the attributes stayed the same. An example of that can be seen in figure 4.2 of the bicycle lane, which runs parallel to the main road, which had the same attributes all the way but was separated before the aggregation. One crucial aspect and the reason this exact aggregation function was used was that it maintained the correct geometries of the aggregated parts, which was needed for length calculations later on. The SwissTLM3D was the second essential road data set with the variable road width, which often had multiple parts per road segment. After filtering the data set's relevant roads and paths, the same aggregation function was applied with the corresponding helper functions for its variables.

4.2.3 Data Matching

The goal of this part was to spatially match all remaining data to the ground network. Some of the more straightforward matching was done prior inside QGIS and included the following variables: speed limit, nearby tram tracks, relevant pedestrian islands, and the planned bicycle network. The reason for that was either the geometries aligned perfectly with the geometries of the base network and were quickly matched with the function *join attributes by location* or that they were variables that were not essential for the network structure and it was much more practical to match them in QGIS just one time. In that way, the Jupyter Notebook was not cluttered with stagnant lines of code of matching functions that never had to be adjusted or changed. In this matching part, the following four data sets needed to be matched to the main network: the SwissTLM3D data sets with the road widths, the traffic model 2018 with the daily traffic flows, car parking spots, and the slope of the road segments.

The slope ultimately was an attribute join, whereas the three other data sets were spatially matched. For the slope preparation, QGIS was used for simplicity and the built-in functions. The triangular irregular network of the digital terrain model of the city of Zurich was turned into a raster with the use of the *TIN interpolation* function.

For every network segment of the ground network, the function *interpolate point on line* interpolated points with a set distance of 3 meters, which were then draped with the z-values of the elevation model. The resulting interpolated points were then read into Python, where a short function calculated the slope between each point and the median of each segment, which were then joined to the ground network. Road segments under 30 meters were then excluded because they were deemed insignificant. First, shorter steep sections are often acceptable for cyclists. Second, the slope calculation of short segments was prone to errors as they sometimes only consisted of very few interpolated points.

For the remaining three data sets, spatial matching needed to be done. Again, a short preparation in QGIS was performed for the parking spots. The parking data set of Zurich was filtered by whether the parking spots would lie on the road and would therefore make the width of the road smaller. This subsetting was done for two reasons: The narrowing of the road would mean a significant increase in the level of traffic stress of cyclists, and a standard of enough space and sufficient view was assumed to be valid for parking spots off the road. This assumption was considered acceptable from the side of the civil engineering office of Zurich. In LTS literature, the distance from the bicycle lane to the parking spots was used as a factor for the classification (Winters et al., 2016), but this was unfortunately not possible in Zurich due to a lack of data. The matching of the parking spots to the ground network was done with a function that buffered the lines of the network and then checked for geometric overlaps with the parking spots. This way, theoretically, a parking spot could be matched to two different network road segments. This was done intentionally because a parking spot near a road intersection impacts not just one of the adjacent roads but both.

For the two data sets with diverging road geometries, a spatial matching function was written. A critical prerequisite for the employed matching style was the previous aggregation of network segment parts into complete segments. As illustrated by figure 4.3, the segmentation of roads from different data sets can pose many problems. Different numbers of features and varying divisions of the same road segment can cause it to be unclear which attributes need to be matched to which part. Although there are different approaches to fixing these problems, the aggregation part of this methodology significantly minimized this problem and simplified the matching process by turning the two geometries of the example in figure 4.3 into one part each.

This led to this work using a relatively simple matching approach that was expanded slightly. The middle point of each segment of the ground network was initially calculated and buffered with a value that can be input into the matching function, e.g., 10m.

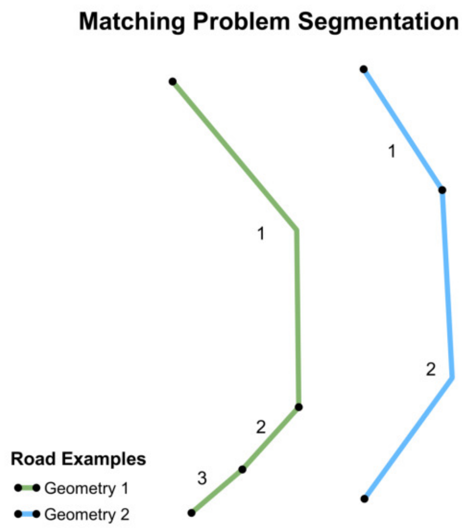

Figure 4.3: Segmentation problem example, fictional roads

Then, overlaps between the buffers and the segments from the data were calculated and sorted after the amount of overlap. This approach matched most segments relatively well. However, some roads perpendicular to the segments of the ground network tended to be matched wrong if they were near the middle and, therefore the buffer of the segment. The function was improved by not only choosing the middle point of the to-be-matched segment but three points on the line, which were placed towards the middle of the segment so as not to create problems at the intersections. This version resulted in the correct matching of these problematic perpendicular roads and was deemed sufficient for this work. This same function matched the SwissTLM3D and the traffic model 2018 to the ground network. With a buffer size of 10 meters, 8458 out of 8618 ground network road segments could be matched with the SwissTLM3D data and 4663 segments with the traffic model 2018 data. This discrepancy is because the SwissTLM3D includes all roads and paths of Zurich, while the traffic model only included certain roads, leading to a lower number of matched segments. For this data set in particular, it was beneficial to only use the three points near the middle of the segment, not to mistakenly match segments based on proximity at a common intersection.

While this way of road matching might not have been perfect and certainly had room for improvement, its improvement would have exceeded the scope of this work. It was, however a limitation that needed to be considered for the rest of the methodology. Its implications will be discussed further in the section 'Limitations'.

4.3 Phase 2: Level of Traffic Stress Classification

This section describes phase 2 of the methodology, the level of traffic stress classification. This part will first illustrate the procedure of the development of the classification. Then, it will give an overview of the criteria used for the classification and how they impact the different LTS groups. After that, the classification schemes for the three classes of bicycle facilities are presented, and finally, the implementation of these classification schemes will be described.

4.3.1 Classification Development

One of the most critical parts of an LTS analysis of a bicycle network are the classification schemes, which decide which road segments are assigned which traffic stress level. As mentioned in the literature review of this thesis, the majority of work done on the level of traffic stress methodology is from the USA. Besides the mentioned differences in data, the road designs and road network designs of the studied cities tend to differ from Zurich's. This meant the following for the development of classification schemes for Zurich:

1. For variables that were the same or similar in existing studies, values needed to be adjusted to fit Zurich's situation.

2. Variables that were unavailable or not applicable to Zurich needed to be substituted or accounted for in some other way.

3. Variables added or specific to Zurich needed to be implemented into the existing schemes.

4. Local knowledge was needed for validating the adapted classification schemes.

The elaboration of the variables from points 1-3 will be found in the following subsection of the LTS criteria. One of the main goals of this work was to make the LTS networks for the LTS groups as realistic as possible, which led the fourth point of this list to be a focal point of interest in developing the classification schemes. Slight variations in the classification scheme could have drastic consequences for certain LTS groups due to everyday road situations being classified one way or another. One way of achieving this goal of realistic classification schemes for Zurich was collaborating with the civil engineering office of Zurich and Pro Velo Zürich. The exchanges were comprised of three meetings each, focussing on the state of the work at the time. The respective first meeting was about the general plan of the thesis and a general discussion of the plans and developments of the bicycle situation in Zurich. The main point of the second meeting was the revision of the first iterations of the classification schemes that were developed. Finally, the third meeting revolved around the results of the work, the planned network analysis, and what additional, more minor questions could be answered with the final analysis tool. Points of discussion regarding the classification of the LTS criteria will be reviewed continually in the following subsections. At the same time, other inputs, ideas, and conclusions of the meetings will be mentioned in the result and discussion part of the thesis. The reason that the civil engineering office and Pro Velo Zürich were selected as points of contact was that they both are very involved and have a lot of experience in bicycle projects in the city. Additionally, with one instance of an administrative office with stricter requirements and orders and one instance of an independent, more politically slanted organisation, different views or even minor disagreements served as an interesting point for discussions.

4.3.2 LTS Criteria

Starting with variables that could be adopted from many different LTS methodologies (Mekuria et al., 2012; Winters et al., 2016; Montgomery County, 2017), the classification included bicycle infrastructure, speed limits, the occurrence of car parking, and the daily motorized traffic volumes. As the literature review mentioned, bicycle infrastructure has one of the most significant impacts on cycling stress levels. Apart from intersection infrastructure, two main types of infrastructure exist: separated bicycle paths and bicycle lanes on the roads. A separated bicycle path is the best way to reduce traffic stress and therefore normatively received a LTS level 1. Depending on the other variables, a bicycle lane on the road was able to receive LTS levels between 1 and 4.

Table 4.1: Impact of bicycle infrastructure on the level of traffic stress groups

Bicycle Infrastructure				
Type	LTS 1	LTS 2	LTS 3	LTS 4
Separated bicycle path	best option	preferred	-	-
Bicycle lane on road	not / rarely bearable	dependant on other variables	mostly acceptable	-

The speed limits of roads were relatively easy to adapt from the studies of the USA to Zurich. 20 miles per hour is very similar to 30 km/h, a common speed limit for Zurich, and 30 mph is similar to 50 km/h. Besides the 30 and 50 km/h speed limits, the only speed limit to consider was 20 km/h, which can be found in zones called 'Begegnungszonen' in Zurich. In these zones, which can be translated to 'encounter zones', pedestrians and bicycles have the right of way. This makes them very safe and suitable for the LTS group 1. Although there were roads with speed limits over 50 km/h in Zurich, apart from 60 km/h, they were neglected as they only served as feeders for highways and were therefore removed from the data.

Table 4.2: Impact of road speed limits on the level of traffic stress groups

Road Speed Limits				
	LTS 1	LTS 2	LTS 3	LTS 4
$\leq$ 20 km/h	suitable	-	-	-
30 km/h	dependant on definition	dependant on other variables	-	-
$\geq$ 50 km/h	not suitable	not suitable	dependant on other variables	-

Parking occurrence increased the level of traffic stress due to three reasons. The first one is that for motorized traffic to get to the parking, they usually have to cross either a bicycle lane or the unsignalised space that cyclists move in where there is no bicycle infrastructure. This crossing on the open road, with the additional stress that a car driver experiences while wanting to park and having to stop the traffic behind them results in accidents or, at best, unpleasant experiences for the cyclists. The second reason is the danger of parked cars to cyclists. With parallel parking spots, the opening doors of cars most commonly intersect the cycling area, and with perpendicular parking, the car driver's vision is usually very limited. The third is a more minor but more specific problem. A typical road situation in Zurich is a residential road with interweaving parking spots that are supposed to slow down the motorized traffic (figure 4.4).

Figure 4.4: Interweaving parking on a residential road

Although being successful at that, for bicycle users of groups 1 and 2, this results in a (too) stressful road as they have to navigate through them while simultaneously dealing with the motorized traffic. These reasons for parking show that all LTS groups have perceived stress connected to parking, although triggered by different situations.

The daily motorized traffic volume was the last variable closely adopted from LTS literature. A classification scheme revised multiple times (Furth, 2022) included many ranges of acceptable ADT depending on the road composition. As we will see shortly, these numbers could not be adopted due to the missing road composition data and were therefore defined in the discussions with the civil engineering office and Pro Velo Zürich. An ADT below 1000 signified low traffic on 30 km/h roads, and 1000-3000 and 3000+ meant medium and high traffic, respectively. Due to a noticeable increase in ADT on roads with speed limits 50+ km/h, an ADT below 5000 was considered 'low', whereas above that number was marked as high. Notably, the ADT variable was only considered relevant in mixed traffic without bicycle infrastructure.

Table 4.3: Impact of the average daily traffic (ADT) on the level of traffic stress groups

Average Daily Traffic				
	LTS 1	LTS 2	LTS 3	LTS 4
≤ 1'000	necessary	-	-	-
1'000 - 3'000	not suitable	mostly acceptable	-	-
3'000 - 5'000	not suitable	rarely acceptable	mostly acceptable	-
≥ 5'000	not suitable	not suitable	not suitable	-

The primary variable that needed to be substituted from the LTS methodologies was the road composition. The number of lanes and the existence of a centerline were not available for Zurich and were therefore replaced with the road composition data of the SwissTLM3D data set. After filtering out irrelevant segments like highways or pull-ins, nine types of segments remained. Five types were roads with differing road widths (3m road - 10m road), two types were paths, one was city squares, and the last was geometry links of the data set. The two path types and city squares were always classified as LTS 1 due to the absend motorised traffic. The geometric link is not a descriptive segment and was therefore classified with the adjacent road segments' lower traffic stress level. Finally, the five types of road widths gave information about the type of road and were classified accordingly, e.g., 8m and 10m roads → main roads with multiple lanes → not suitable for LTS groups 1 and 2. Contraflow lanes were an additional type of road composition in the literature. These roads were identified using the 'one-way' attribute of the roads with the directions of the cycling network and received their own part in the classification scheme.

Table 4.4: Road composition types of the SwissTLM3D data set. Note: The description refers to the most common road of this type, can differ due to unusual road geometries. Road widths include a range, e.g. 3m road = 2.81m - 4.2m roads

SwissTLM3D Types		
	Description	LTS
3m road	narrow side roads	see classification schemes
4m road	side and residential roads where cars can cross	see classification schemes
6m road	main and residential roads, where traffic flows freely	see classification schemes
8m road	main roads, sometimes multiple lanes	see classification schemes
10m road	main roads, multiple lanes	see classification schemes
1m path	narrow paths, not accessible by car	LTS 1
2m path	wider paths, rarely accessible by car	LTS 1
square	public squares	LTS 1
link	link between unconnected geometries	LTS of lowest adjacent edge

The remaining three variables tram tracks, pedestrian islands, and slope are all additional variables to the existing LTS literature. Because they would not impact the road situation in combination with, but just in addition to the other attributes, they were applied after the rest of the classification schemes onto the road segments. Tram tracks have shown to be correlated to bicycle accidents in Zurich (Biland, 2023) due to situations like the one in figure 4.5, where there is not enough space, mostly due to tram stations and bicycle wheels can get caught in the tracks. Road segments, which were in a buffer of 3 meters of tram tracks and lied in that buffer with at least 50% of their length, were chosen to be impacted by the tracks. This safety hazard was deemed unacceptable for low-stress cycling. Therefore, all segments with LTS 1 and 2 impacted by tram tracks went up to LTS 3. As tram tracks are however not only dangerous for LTS groups 1 and 2, but also due to higher speeds for groups 3 and even 4, impacted road segments with LTS 3 moved up to LTS 4.

Pedestrian islands, although making the road crossing safer for pedestrians, often pose another danger for cyclists in Zurich. By narrowing the road by up to two meters, it is often too narrow to fit a bicycle beside a car, and they have to pass by the

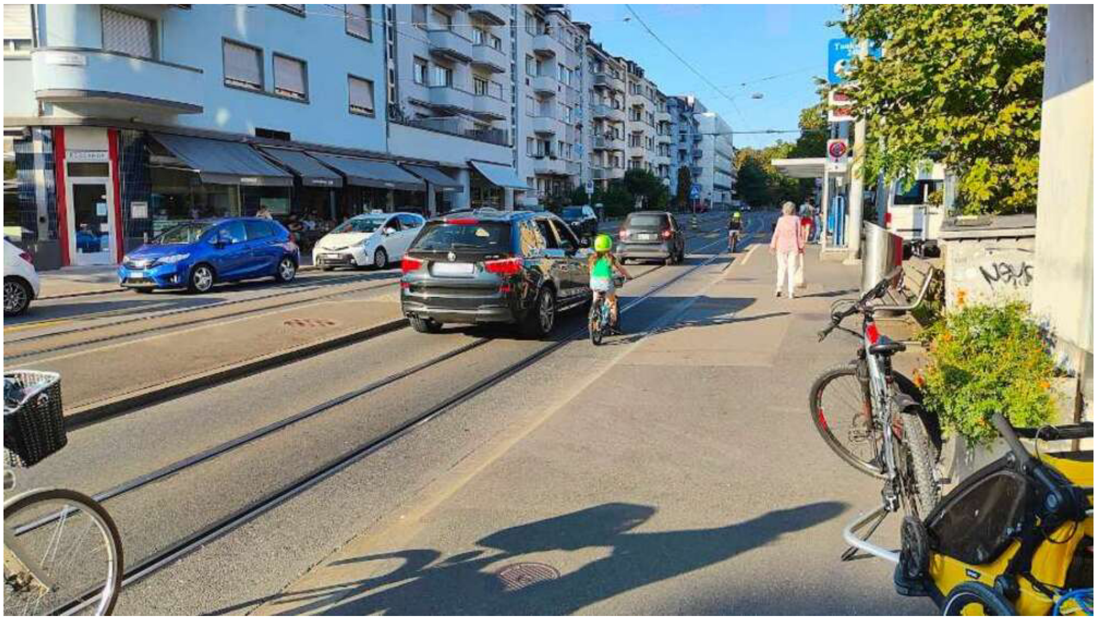

Figure 4.5: Tram station with dangerous tram tracks, high curbs and narrow road width. Source: bikeable.ch, user: stefanhaustein

pedestrian island sequentially. This also means that sometimes, car drivers speed up and try to overtake cyclists right before the island, leading to dangerous, uncontrollable situations for cyclists. In addition, due to strict regulations of how much space is needed for putting down the markings for bicycle lanes on the road, the bicycle lanes often cease to exist a few meters before the pedestrian island and start appearing again a few meters later (figure 4.6). Due to this safety hazard, all road segments with a pedestrian island that laid entirely inside the road and therefore narrowed the road's width received an increase of one stress level.

The last variable, the slope, was highly discussed with the civil engineering office and Pro Velo Zürich. A steep upward slope generally increases the stress on cyclists (Matias and Virtudes, 2020) but does not impact all LTS groups the same. For the LTS groups 1 and 2, the difficulty of handling the bicycle is increased in addition to a tendency of lower levels of power and fitness. This fact meant that for groups 1 and 2, steep slopes above 5° meant an increase in the LTS level. However, the current emergence of the electric bicycle counteracts some of the reasons why the LTS level should be raised. Older people and generally more uncomfortable riders are realistically the ones who ride an electric bicycle, reversing the need to include the slope as a variable. This work ended up implementing both versions in the classification, which enabled the analysis of both versions and the option of using both versions in the future, depending on

Figure 4.6: Interruption of bicycle lanes and road bottleneck due to pedestrian island. Source: bikeable.ch, user: lee_

the future significance of the variable. As there are significant gradients in the city of Zurich and Menghini et al.'s work (2010) deemed it as a relevant variable for route choice in Zurich, it was included in the baseline classification of the LTS network.

Table 4.5: Impact of additional variables on the level of traffic stress groups

Impact Additional Variables				
	LTS 1	LTS 2	LTS 3	LTS 4
Tram Tracks	up to LTS 3	up to LTS 3	up to LTS 4	-
Pedestrian Islands	up to LTS 2	up to LTS 3	up to LTS 4	-
Upward Slope (optional)	up to LTS 2	up to LTS 3	-	-

4.3.3 Intersections

In contrast to a lot of LTS literature, this work did not classify the intersections of the network. This decision was based on two main reasons. The first one is a lack of data on intersection bicycle infrastructure. In the last few years, a considerable effort has been made in Zurich to build intersection infrastructure like bicycle pocket lanes for easier left turns or new signals that allow turning right at a signalised crossing with a red signal. However, a data set with the locations of those intersections was not available. It is essential to realise that intersection infrastructure can only make the crossing as good as the best adjacent road due to the logic of the weakest link principle. The second reason for excluding the intersections is that Zurich has many traffic lights and therefore signalised crossings, which do not increase the level of traffic stress (Mekuria et al., 2012). Due to the principle of installing traffic lights wherever it is unsafe, the need for an in-depth analysis of the intersections in Zurich was deemed unnecessary. Classifying unsignalised crossings for roads with up to 6+ lanes (Mekuria et al., 2012) was also unnecessary for Zurich, as such crossings do not exist in the city's road infrastructure.

4.3.4 LTS Classification Schemes

In accordance with the above-described variables, there are two resulting classification schemes, one for roads with bicycle lanes and one for mixed traffic without any bicycle infrastructure. The road segments with bicycle lanes ended up relatively straightforward, with most roads with a speed limit of 30km/h as LTS 2 and all roads with speed limit $\geq$ 50km/h classified as LTS 3.

Road Segments with Bicycle Lanes

Speed Limit (km/h)	Street Width (m)	No Parking	Parking	Contraflow lane
20	NA		LTS 1	
30	3	LTS 2	LTS 2	LTS 3
	4	LTS 2	LTS 2	LTS 3
	≥ 6	LTS 2	LTS 2	LTS 2
≥ 50	≤ 4	LTS 3	LTS 3	LTS 3
	6	LTS 3	LTS 3	LTS 3
	8	LTS 3	LTS 3	LTS 3
	10	LTS 3	LTS 3	LTS 3

Figure 4.7: Classification scheme for roads with bicycle lanes. Reminder: The assigned LTS group indicates the lowest group, that feels comfortable in the segments in question.

The only cell that seems out of order is the contraflow lane on a 30km/h road and a road width of ≥6m. This is based on the knowledge that there are no contraflow lanes with multiple lanes in Zurich. Therefore, those segments are relatively wide roads with only one lane, which negates the usual problem of contraflow lanes, where there is barely enough space for a car and bicycle to pass each other.

The second classification scheme targets the roads with mixed traffic without any bicycle infrastructure. This scheme is more intricate, mainly due to the daily motorized traffic variable. One of the bigger discussions with the civil engineering office was the significance of the ADT in certain road situations.

<table>
<tr><th colspan="9">Mixed Traffic</th></tr>
<tr><th rowspan="2">Speed Limit (km/h)</th><th rowspan="2">Street Width (m)</th><th colspan="3">No Parking</th><th colspan="3">Parking</th><th rowspan="2">Contraflow lane</th></tr>
<tr><th>ADT < 1'000</th><th>ADT 1'000 - 3'000</th><th>ADT > 3'000</th><th>ADT < 1'000</th><th>ADT 1'000 - 3'000</th><th>ADT > 3'000</th></tr>
<tr><td>20</td><td>NA</td><td colspan="7">LTS 1</td></tr>
<tr><td rowspan="3">30</td><td>3</td><td>LTS 1 / LTS 2</td><td>LTS 2</td><td>LTS 2</td><td>LTS 2 / LTS 3</td><td>LTS 3</td><td>LTS 3</td><td>LTS 3</td></tr>
<tr><td>4</td><td>LTS 1 / LTS 2</td><td>LTS 2</td><td>LTS 3</td><td>LTS 2 / LTS 3</td><td>LTS 3</td><td>LTS 3</td><td>LTS 3</td></tr>
<tr><td>≥ 6</td><td>LTS 1 / LTS 2</td><td>LTS 2</td><td>LTS 3</td><td>LTS 2 / LTS 3</td><td>LTS 3</td><td>LTS 3</td><td>LTS 3</td></tr>
<tr><td rowspan="5">≥ 50</td><td>≤ 4</td><td>LTS 3</td><td>LTS 3</td><td>LTS 3 / LTS 4</td><td>LTS 3</td><td>LTS 3</td><td>LTS 4</td><td>LTS 4</td></tr>
<tr><td>6</td><td>LTS 3</td><td>LTS 3</td><td>LTS 3 / LTS 4</td><td>LTS 3</td><td>LTS 3</td><td>LTS 4</td><td>LTS 4</td></tr>
<tr><td></td><td colspan="2">ADT < 5'000</td><td>ADT > 5'000</td><td>ADT < 5'000</td><td colspan="2">ADT > 5'000</td><td></td></tr>
<tr><td>8</td><td colspan="2">LTS 3</td><td>LTS 4</td><td>LTS 3</td><td colspan="2">LTS 4</td><td>LTS 4</td></tr>
<tr><td>10</td><td colspan="2">LTS 3</td><td>LTS 4</td><td>LTS 3</td><td colspan="2">LTS 4</td><td>LTS 4</td></tr>
</table>

Figure 4.8: Classification scheme for roads with mixed traffic

Originally adopted from one of the most recent iterations of Furth's LTS classification tables (2022), a low speed limit and a low ADT are sufficient for the LTS group 1. However, this did not resonate with both the civil engineering office and Pro Velo Zürich, which led to further discussions about certain road situations and ultimately prompted this work to implement both versions. For the cells where it is relevant, the version with high ADT significance is bold in the figure 4.8, whereas the version with low ADT significance is written normally. Due to the similarity to the LTS classification, which was revised multiple times over the years (Furth, 2022), the classification with the high ADT significance was chosen as a baseline.

4.3.5 Implementation

The implementation of phase 2 was relatively straightforward. In preparation for the classification function, all variables were checked for problematic values and fixed accordingly. Each variable was looked at individually and cleaned up in a way that made the most sense for the classification function. This often meant changing the None values to 0, especially for variables, for which it made sense thematically that an if clause in the classification function can check for $\leq$ instead of having an additional if statement for those values. A special case was the road composition variable originally from the SwissTLM3D data set. Because the network of the SwissTLM3D is generally much finer than the ground network, every road segment that could not be matched to the ground network from the SwissTLM was a small path, usually in the forest. Consequently, all *None* from the variable road composition were labeled as 'not_matched' and later assigned a level of traffic stress 1.

After the preparation of the variables, the data set was converted into a bidirectional data set. This was achieved through a function that first checked which roads were one-way and which were two-way. Then, it doubled the two-way roads, and together with the roads that were one-way and against the direction of the geometry, it reversed all their directional variables, slopes, and geometries. After that, it was ready for the LTS classification.

The classification of the road segments was straightforward, as it was a long sequence of conditionals that needed to be arranged in proper order. Notably, as mentioned before, the classification function was implemented in a way that leaves room for some decision-making. The function takes the following arguments as inputs:

```
lts_classification(road_network, classification_tables,
    ADT_significance = 'high', slope_inclusion = False,
    planned_network = False, planned_network_classification
    = None)
```

The argument ADT_significance and the inclusion of the slope were discussed in the section 'LTS Criteria'. The planned_network argument and the corresponding classification argument will be discussed in the section 'Planned Network Exploration'. Besides the self-explanatory road_network, the classification_tables are the two LTS classification schemes. They were included as an input variable so that it would be possible to easily change the single cells of the LTS classification schemes if needed.

4.4 Phase 3: Connectivity & Accessibility Measures

In phase 3 of the LTS analysis, two network measures were calculated. First, a connectivity measure was adopted from previous research, and second, a slightly adapted accessibility measure was implemented. To prepare the classified data set for network analyses, it first had to be converted into a bidirectional network graph with the NetworkX package. After that, it was split into four different networks, one for each LTS group. The road segments that exceeded the respective level of traffic stress were not removed from the networks but instead drastically weighted according to the deviations of the LTS levels. For both the connectivity and accessibility measures, the principle of the weakest link is essential. Trips with parts of exceeding traffic stress render the whole trip unsuitable.

4.4.1 Connectivity

The connectivity measure was set up according to low-stress connectivity literature (Winters et al., 2016; Lowry et al., 2016). It consisted of shortest path generations within the respective LTS networks, which were additionally limited to a maximum acceptable detour compared to the shortest path without any LTS considerations. The acceptable amount of detour was defined as ≤500 meters for shorter trips and 1.25 times the shortest path for longer trips. For the trip generation, a random node of the network was chosen, and a random second node was defined within a buffer of a chosen distance. Simultaneously, the absolute shortest path and the weighted LTS shortest path were calculated, compared to each other, and placed into one of the following categories: trip connected, trip unconnected due to LTS, and trip unconnected due to excessive detour. After repeating this process n amount of times, the connectivity measure (C_n) was simply the number of connected trips (T_{con}) in comparison to the unconnected trips due to an excessive amount of traffic stress (T_{lts}) plus the unconnected trips due to detour (T_{det}).

$$C_n = \frac{\sum T_{con}}{\sum T_{lts} + \sum T_{det}}$$

Besides the distance of the buffer and the number of iterations, the connectivity measure function takes an argument of the 'LTS barrier'. This variable defines if the LTS barrier is 'hard', which means that no road segment with higher LTS can be passed through, or 'soft', which allows the trip to once pass through a segment of one level of traffic stress higher than comfortable. This is achieved through the weights in the preparation part of the networks and the NetworkX *single source dijkstra* function with a specific cutoff. The use of the soft LTS barrier was deemed reasonable due to two reasons. First, it is realistic that a percentage of people who feel uncomfortable on a short segment of their bicycle trip would stop and walk this part of the trip. Second, and this will be discussed further in the 'Limitations' part of this thesis, some short segments of the road network were bound to be poorly matched due to the matching algorithms and the different data sets. This meant that some short segments with an important low-stress link function received a level of traffic stress that was too high. Setting the LTS barrier to soft could alleviate this fact by once 'ignoring' such a segment. For an assessment of the stability of the connectivity measure and the network model, a Monte Carlo simulation was set up.

4.4.2 Accessibility

The accessibility measure was a further development of the connectivity measure. As origin data, the buildings of Zurich were used, and the destination data was a filtered part of the points of interest (POI) of the OpenStreetMap data set. In accordance with Kent & Karner (2018), destination points were chosen to be equally suitable for all citizens. Specific needs or leisure time destinations were therefore not included. This resulted in the following five categories: educational facility, medical facility, bank, supermarket, and public transport infrastructure. The function chooses a random point from the origin data and a destination point of the points of interest inside a buffer of the input distance. From there, the same procedure as in the connectivity measure was applied, and the same final metric was calculated. However, in the accessibility function, there are a few additional input options:

```
accessibility_measure(network, start_points, poi,
    n_iterations, distance, lts_barrier = 'soft', poi_type
    = None, neighbourhood = None, district = None,
    nearest_poi = False, output = True)
```

The *poi_type* variable can subset the destinations into one of the five categories of points of interest, while the *neighbourhood* and the *district* variable can reduce the size of the study area and therefore the origin points to a neighbourhood or district. The *nearest_poi* argument defines if a random point should be chosen inside of the buffer or if it should choose the geographically nearest poi. For a more general assessment of the accessibility and significant increase in computing time, especially with high numbers of iterations, this variable was turned to False per default. These four variables are good examples of the goal of what the Jupyter Notebook was trying to achieve: to be a tool that can give answers to different questions. Without these variables, this function answered the question of how accessible points of interest are in general in the city, whereas with the inputs of *district* = 'Kreis 1', *poi_type* = 'supermarket' and *Nearest_poi* = 'True', the function was, for example, able to go very in-depth on the accessibility to the nearest supermarkets in the district 'Kreis 1'.

4.5 Phase 4: Results Generation & Planned Network Analysis

Phase 4 consists of two parts. The first one used the implemented functions from phase 3 to create different results for different questions. The second part centered around the planned network of the city of Zurich. Different deviated instances of the LTS classification were calculated and then analysed in the same manner as the current state of the bicycle network.

4.5.1 Results Generation

This section of the Jupyter Notebook brings back the comparative aspect of the different levels of traffic stress groups. The connectivity overview and comparison function calculated the connectivity measure for all four LTS groups simultaneously and supplied a simple table of percentages of connectivity, unconnected trips due to LTS, and unconnected trips due to detours for all four LTS groups. The same function was set up for the accessibility measure. For both functions, the options of using the additional variables were still available. Ultimately, all connectivity and accessibility overview functions were run multiple times with different distance inputs to see their variations over different trip lengths.

To analyse the spatial variations of the accessibility measure, a function was set up to run the accessibility measure for all spatial divisions, either districts or neighbourhoods. All the same inputs were able to be used to achieve the same desired level of detail. Notably, this function only shows the spatial variation in districts or neighbourhoods for one LTS group per calculation.

4.5.2 Planned Network Exploration

As mentioned in the chapter 'Study Area', the planned bicycle network of Zurich consists of three parts: the fast routes, the base network, and the main network. After discussions with the civil engineering office and Pro Velo Zürich, there seemed to exist different expectations of what these networks were supposed to deliver in the future. Obvious connections could be made to which networks were supposed to be suitable for which types of cyclists, which led this work to an additional analysis of the planned network. In the end, two different versions of expectations and goals of the planned network were worked out. The first version focused only on the fast routes that should be completed by 2030. These routes claim to be suitable for all kinds of bicycle drivers and were therefore classified as LTS 1. The second variation placed a further emphasis on the base network of the planned bicycle network of the city. As the goal of the base network is the fine-granular extension of the fast routes that allow everybody to reach their goals, the network edges of the base network were also classified as LTS 1. The remaining network edges were classified in the same way as in the analysis of the current network. For each of those versions, the LTS classification function, with the previously mentioned additional variables *planned_network* = True and the corresponding classification dictionary *planned_network_classification* calculated a new version of the road network. Like the original network, they were converted into NetworkX graphs, weighted, and split into the four LTS networks. Finally, they were able to be analysed in the same way as the current state of the bicycle network.

5 Results

The results of the thesis consist of three sections: First, the LTS classification and the resulting four networks of the different LTS networks will be explored. Then, the connectivity and accessibility analyses of the networks will be displayed. Finally, the results of the modeled planned network will be featured.

5.1 LTS Networks

The upcoming results were created through the baseline of the LTS classification function with the variable ADT significance on high and with the inclusion of the slope. The differences to versions with the ADT significance on low (ADT low) and the exclusion of the slope (no slope) will be included for comparison, where this work will see fit. This resulted in the following level of traffic stress distribution of the network edges:

Table 5.1: Network edge distribution regarding level of traffic stress, baseline classification and both the no slope and the ADT low classification

Network Edge Distribution				
	n	p	no slope	ADT low
LTS 1	6197	38.35%	41.92%	25.13%
LTS 2	3693	22.85%	20.56%	19.31%
LTS 3	3526	21.82%	20.54%	41.66%
LTS 4	2743	16.98%	16.98%	13.9%

With the baseline inputs, the biggest share of 38.85% of network edges was assigned LTS 1, whereas LTS 2 (22.85%) and 3 (21.82%) had similar shares. The remaining 16.98% were classified as level of traffic stress 4. The exclusion of the slope shifted 1.28% of the total network edges from LTS 3 to LTS 2 and 2.29% from LTS 2 to LTS 1. A drastically different picture paints the distribution of network edges of the classification with ADT significance set to low. Only slightly over a fourth of the network edges were classified as LTS 1, while the number of segments assigned the level of traffic stress 3 almost doubled (41.66%). Due to the shares of LTS 2 and LTS 4 only sinking by around 3 percent compared to the baseline classification, there seems to be a shift from LTS 1 to LTS 3, which is however impossible with the classification schemes. A drastic shift between LTS 1 and LTS 2 co-occurred with a strong shift from LTS 2 to LTS 3. The amounts of occurrences of the specific road compositions were calculated simultaneously as the classification and are visualised in figure 5.1 and 5.2.

The distribution of road segments with bicycle lanes follows clear trends. Overall, many more segments with bicycle lanes do not have car parking nearby (647 - 79). However, if they do, it is much more likely to be a road with a speed limit of 30km/h than ≥50km/h. There is an overall trend regarding the width of the roads and the occurrence of a bicycle lane. There are increasingly more occurrences of road segments with bicycle lanes on wider roads than there are on narrower roads. This trend may however just suggest that bicycle lanes are more often built on more dangerous, wider roads.

Distribution Road Segments with Bicycle Lanes

Speed Limit (km/h)	Street Width (m)	No Parking	Parking	Contraflow lane
20	NA		15	
30	3	13	0	3
	4	27	12	52
	≥ 6	136	39	24
≥ 50	≤ 4	98	6	9
	6	58	5	3
	8	103	6	3
	10	212	11	0

Figure 5.1: Distribution of road segments with bicycle lanes in the classification scheme

The numbers of the road segment composition of roads with mixed traffic, on the other hand, do not follow clear trends but rather represent which kinds of roads are common in the city of Zurich. Overall, there are more than double the number of road segments with a speed limit of 30km/h (7450) than road segments with a speed limit of ≥50km/h (3265). Notably, the ratio and amounts of, for example, road segments with a speed limit of 30km/h to a speed limit of 50km/h do not precisely reflect the total amount of those roads. There might exist much smaller network segments on 30km/h roads than on 50km/h roads and, therefore, might distort the perception of this distribution table.

Distribution Road Segments in Mixed Traffic

Speed Limit (km/h)	Street Width (m)	No Parking			Parking			Contraflow lane
		ADT < 1'000	ADT 1'000 - 3'000	ADT > 3'000	ADT < 1'000	ADT 1'000 - 3'000	ADT > 3'000	
20	NA	332						
30	3	1100	15	109	78	4	2	17
	4	1122	182	188	2047	306	65	284
	≥ 6	151	155	522	657	215	148	83
≥ 50	≤ 4	400	62	428	320	56	27	61
	6	62	61	335	104	45	52	39
		ADT < 5'000	ADT > 5'000		ADT < 5'000	ADT > 5'000		
	8	59	261		63	42		4
	10	94	629		19	37		5

Figure 5.2: Distribution of road segments with mixed traffic in the classification scheme

A section of 4 x 3 km in the center of Zurich was chosen for the following visualisations of the different level of traffic stress networks, followed by an overview of the whole city. The map of the network segments with level of traffic stress 1 (figure 5.3) paints a picture of a very disconnected network with parts spaced apart and cut up. Although certain longer sections with specific objectives can be identified, e.g., a long stress-free leisure segment around the lake, for the most part, the segments are often just short, unconnected sections.

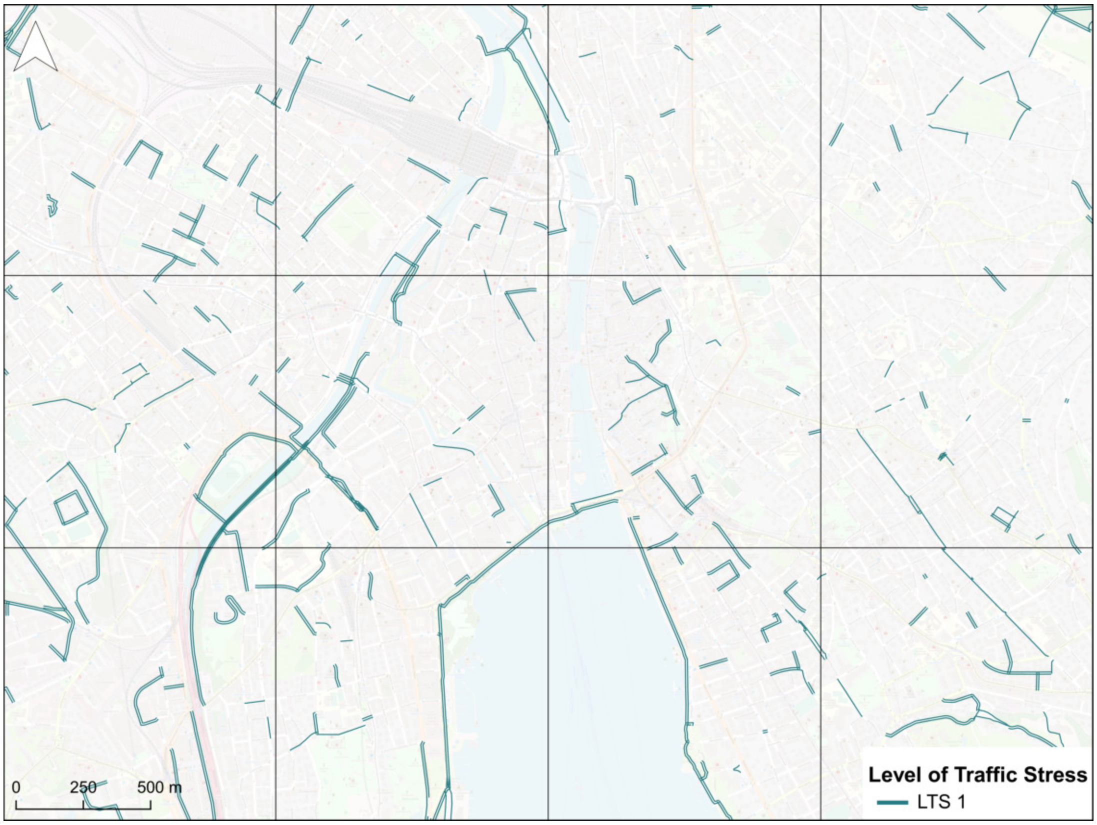

Figure 5.3: Network for the level of traffic stress group 1, section from city centre

With the inclusion of the network segments assigned a level of traffic stress 2 (figure 5.4, some of the sections of LTS 1 were linked together. However, the resulting small groups stayed largely unconnected to each other, constructing low-stress connectivity islands. In the left-most and right-most squares, more LTS 1 and 2 segments can be found than in the four middle (top) squares, which can be described as the city center. Obvious barriers of segments with high levels of traffic stress can be identified all over this section of Zurich but especially around the center, which serves not only as an essential destination but also as a critical bottleneck between the two sides of the river that splits the city into two parts.

Figure 5.4: Network for the level of traffic stress group 2, section from city centre

The segments of level of traffic stress 3 fill the majority of gaps of the low-stress connectivity islands of the previous map. Although the connections between those islands are not the most direct, they are usually possible with a detour. This is the first map that visually resembles a cohesive network (figure 5.5). For specific parts of the overlayed map grid, like the left-most middle square or the right-most middle square, this network is fully functional. Even though in both examples, two main roads are missing, nearby roads present stress-free and fast alternatives.

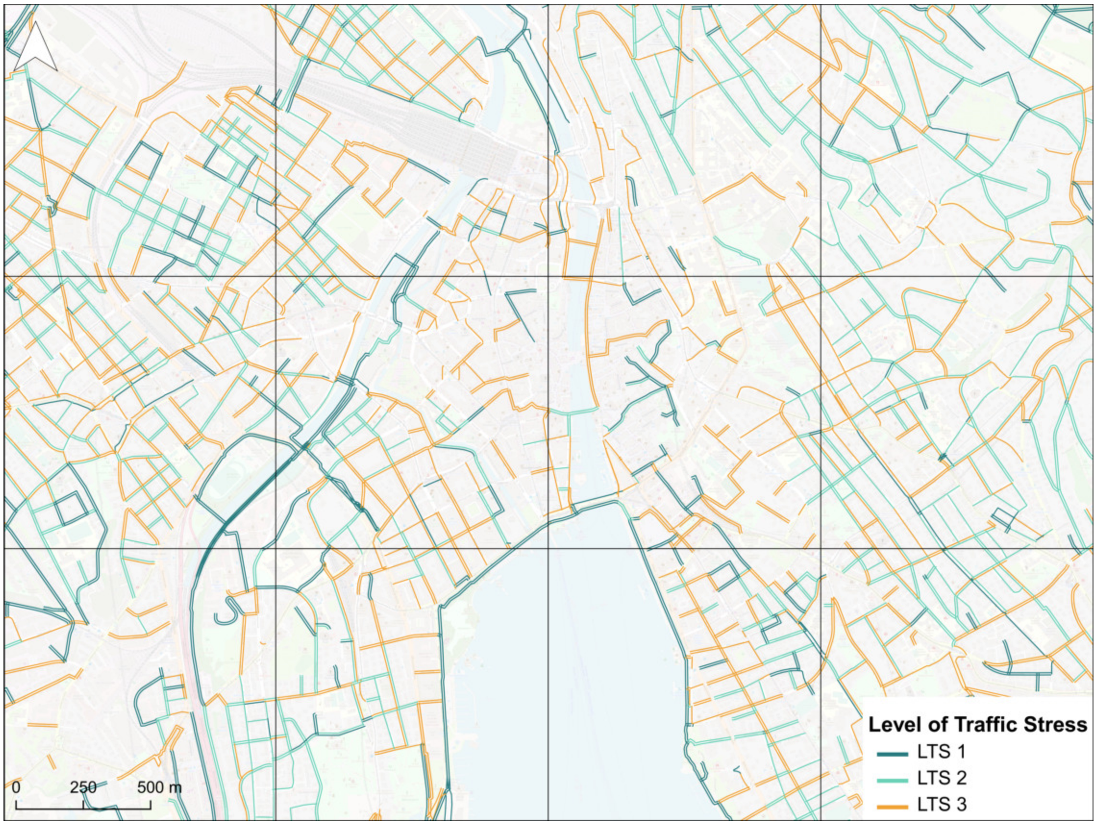

Figure 5.5: Network for the level of traffic stress group 3, section from city centre

The last map finally includes the level of traffic stress 4 and therefore contains all the remaining roads (figure 5.6). The main traffic axes are available, and therefore, not only a cohesive network but also a direct network is to be found. Cyclists of this level of traffic stress tolerance might have a direct and cohesive network but are still prone, if not more prone, to safety hazards on the LTS 4 roads and therefore would profit if the number of those network segments would be reduced.

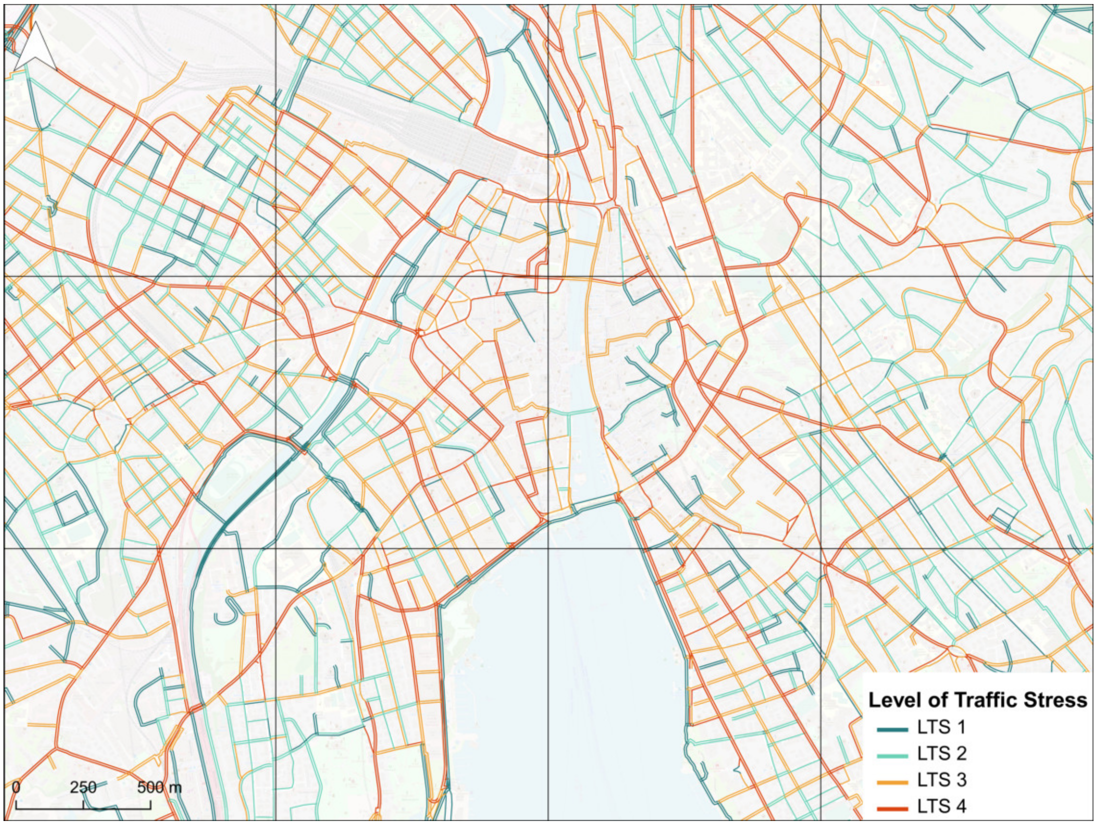

Figure 5.6: Network for the level of traffic stress group 4, section from city centre

Additional patterns can be identified in the map of the whole city of Zurich (figure 5.7). There is a clear trend of roads with higher levels of traffic stress towards the center of the city, with the main traffic axes of LTS 4 leading there from all districts. Due to the forest on the hills and small mountains and their recreational paths, there are considerable patches of LTS 1 on the 'Zürichberg' in the east of the city, the 'Uetliberg' in the south-west and the 'Käferberg' in the north of the city. Additionally, the districts outside the city center tend to have many more network components assigned level of traffic stress 2.

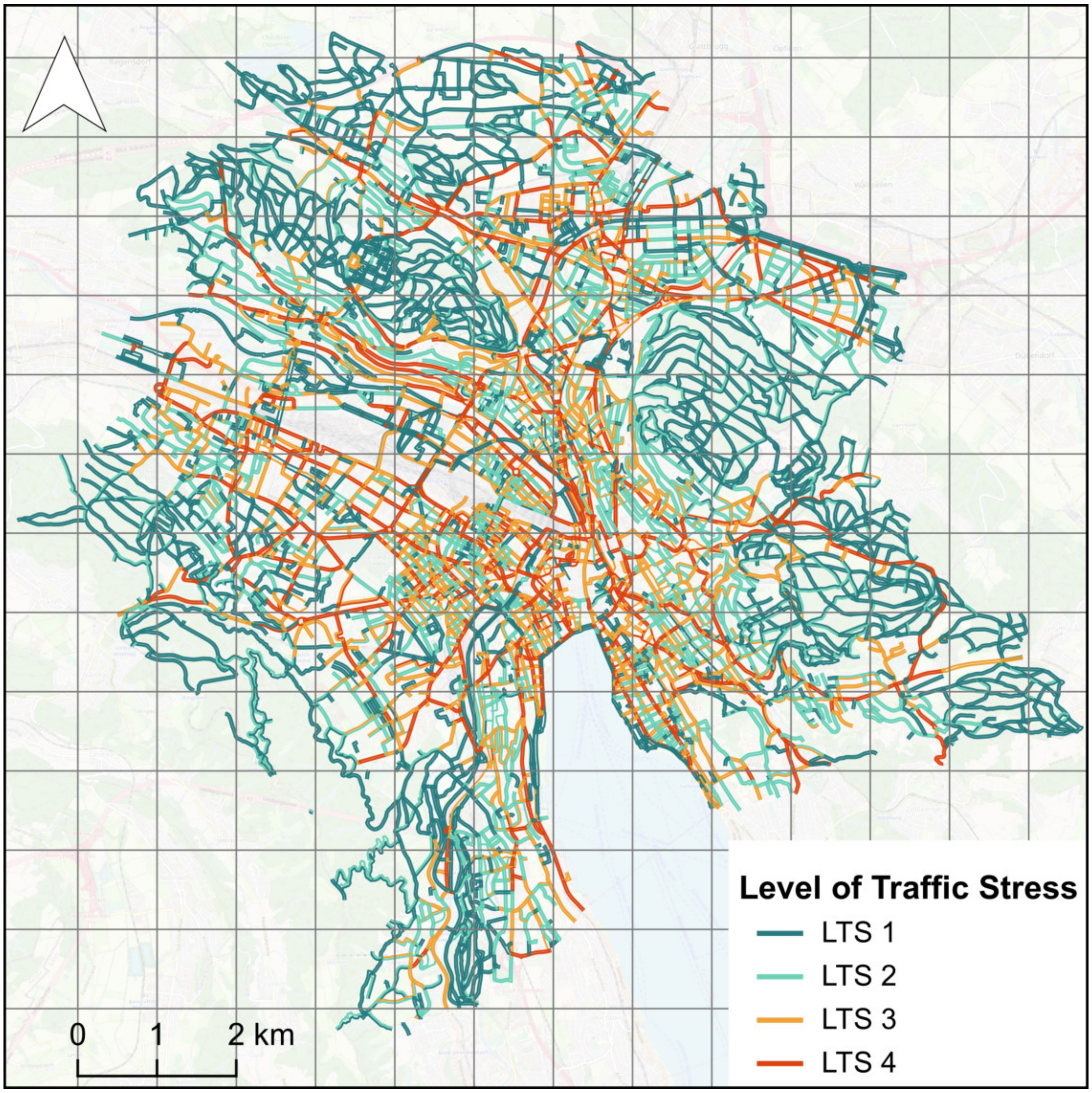

Figure 5.7: Level of traffic stress network overview of the whole city

5.2 Network Connectivity

For the first network connectivity analysis, the baseline classification of a high ADT significance and the inclusion of slope was used. For the following table 5.2, the LTS barrier was set to soft, and an average length of a bicycle trip in Europe of 3 km (European Commision, 2023) was input. The number of generated trips was set to 10'000 for each LTS. Throughout the connectivity and accessibility results section, the level of traffic stress group 4 will generally not be discussed as their results will always be 100%. However, for completeness' sake, the tables will still include the results of the LTS group 4.

Table 5.2: Connectivity overview of the different level of traffic stress networks, trip lengths = 3km

Connectivity Overview			
	connectivity	unconnected LTS	unconnected detour
LTS 1	3.88%	94.58%	1.54%
LTS 2	13.69%	76.30%	10.01%
LTS 3	46.34%	4.78%	48.89%
LTS 4	100.00%	0.00%	0.00%

With these variables, the number of connected trips for the level of traffic stress group 1 amounted to just over 3%. Together with the LTS group 2, which together form the target of low-stress cycling, a connectivity of 13.69% was calculated. This means that about every 7 out of 8 trips of an average length, the citizens of groups LTS 1 and 2 can not absolve due to an exceeding amount of traffic stress, even with the soft LTS barrier of being able to once cross a section of a higher traffic stress level. This number rises to just over 46% for cyclists with a traffic stress tolerance level of 3.

The number of trips that are unconnected due to an excessive amount of traffic stress is the main reason for the low connectivity of the groups LTS 1 and 2, with 94.58% and 76.30% respectively. For the LTS group 3, this number sinks drastically to just 4.78%. The unconnected trips due to a disproportionate amount of detours however rise just as significantly. This shows, as the LTS 3 network map (figure 5.5) suggested, that usually, the cyclists of LTS 3 can find a way to their target without exceeding their traffic stress level, but often the path is not direct and, like the table suggests not direct enough for half of the trips (46.34% connected - 48.89% unconnected due to detour).

The average trip length of 3 km might not fit every bicycle use, especially for the LTS groups 1 and 2. They would much more likely use the bicycle for shorter trips, for example, to the school for LTS 1 or to a supermarket for LTS. For the following figure 5.3 therefore, the same 10'000 trips for each LTS group were calculated for three additional lengths: 1km, 2km, and 5km.

Table 5.3: Connectivity per trip length of the different level of traffic stress networks, baseline classification

Connectivity per trip length				
	trip lengths			
	≤ 1 km	≤ 2 km	≤ 3 km	≤ 5 km
LTS 1	14.50%	6.76%	3.88%	1.76%
LTS 2	30.81%	18.58%	13.69%	7.72%
LTS 3	65.16%	52.01%	46.34%	39.05%
LTS 4	100.00%	100.00%	100.00%	100.00%

As one could expect, the connectivities of the individual networks all get lower, the longer the possible trip lengths are. One thing to note is that the trips are still generated to a point in a buffer from a randomly chosen first point, which means that the ranges are not between the different trip lengths but always from 0 meters to X meters. One significant trend that is logical but has real-world implications is that the lower the traffic stress level is, the stronger it is impacted by increased trip lengths. The connectivity is halved every time throughout these different trip lengths to the next one for the LTS group 1. Although the absolute amount of decrease in connectivity for LTS 3 is higher, the relative amount is much smaller, with LTS 2 staying in the middle of both the relative and absolute measures. This concludes that depending on the LTS group, the use of the bicycle is also strongly influenced by the distance of travel.

Table 5.4: Connectivity per trip length of the different level of traffic stress networks, ADT low classification

Connectivity per trip length (ADT low)				
	trip lengths			
	≤ 1 km	≤ 2 km	≤ 3 km	≤ 5 km
LTS 1	10.05%	5.24%	3.4%	1.41%
LTS 2	21.37%	11.64%	7.84%	3.62%
LTS 3	72.92%	64.08%	59.81%	53.91%
LTS 4	100.00%	100.00%	100.00%	100.00%

Similar results are achieved with the same connectivity measure with a low ADT significance. The trends mentioned above can also be found in table 5.4. Generally, the connectivity of the LTS network 1 and 2 is lower than those from the baseline classification, while the connectivity for the LTS group 3 is higher. This was to be expected as the distribution of network edges went down for LTS 1 and 2, and the share went up for LTS 3. However, the connectivity of the LTS 2 and 3 networks peak an interest. The share of LTS 2 network edges only went from 22.85% to 19.31% between the baseline classification and the ADT low classification but saw a decrease of almost a third (30.81% to 21.37%) in the connectivity measure. Conversely, the connectivity measure of LTS 3 only rose from 65.16% to 72.92%, which seems low for the almost doubled share of network edges (21.82% to 41.66%). This concludes that the network parts, which are classified differently depending on what ADT significance is chosen, have a strong influence over the resulting connectivity of the two groups LTS 2 and 3, and less so over the connectivity of LTS group 1.

5.3 Stability of Connectivity Function

A Monte-Carlo simulation was carried out to assess the connectivity function's consistency. It had two main goals: To check if the results of the connectivity measure were normally distributed and to roughly assess how many trips would need to be generated to achieve reasonable uncertainties. Simply put, the simulation generated a large number of connectivity measures and assessed the variations and the averages of their outputs.

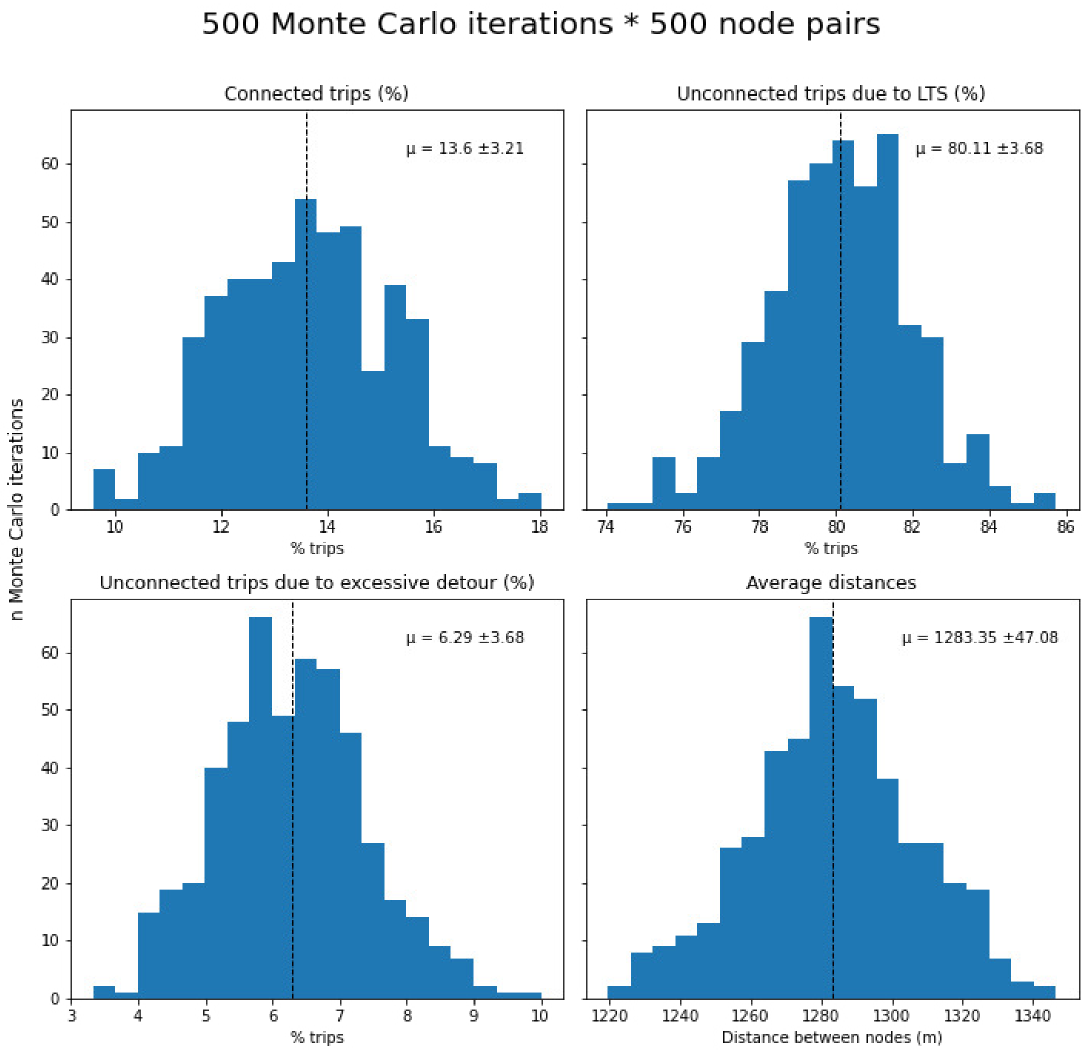

Figure 5.8: Distributions of the Monte Carlo simulation per variable of the connectivity function output

Figure 5.8 shows a convergence to a bell curve for the three outputs of the connectivity function and additionally the average trip lengths. A normal distribution can therefore be assumed. With just 500 iterations of the connectivity measure with 500 node pairs, the uncertainties of the respective variables are very high. With higher amounts of node pairs, these uncertainties are significantly reduced. Table 5.5 shows that with a trip amount of 10'000, every uncertainty lies under one percent, which was deemed acceptable. In the further process of the thesis, this number was then set as a standard for the amount of trips for function inputs.

Table 5.5: Uncertainties of different Monte Carlo simulations with differing iterations numbers and connectivity trips

Uncertainty Deviations			
it x trips	connected trips	unconnected LTS	unconnected detour
500 x 500	13.6% ± **3.21**	80.11% ± **3.68**	6.29% ± **3.68**
100 x 5'000	14.6% ± **0.95**	77.72% ± **1.11**	7.68% ± **1.11**
50 x 10'000	13.65% ± **0.7**	80.07% ± **0.87**	6.28% ± **0.87**

5.4 Network Accessibility

The accessibility function was designed to answer more specific questions in the four LTS networks. First, however, the baseline inputs will be determined for the accessibility part of the analysis. Like in the connectivity analysis, the LTS barrier was set to soft. Per default, the nearest POI variable is set to False to get an overview of how accessible the points of interest are in general.

The overview of the accessibility of the different LTS networks with different trip lengths shows a drastic decrease in the share of connected trips compared to the connectivity analysis with the same variables.

Table 5.6: Accessibility per trip length for the different level of traffic stress networks, baseline inputs

Accessibility per trip length				
	trip length			
	≤ 1 km	≤ 2 km	≤ 3 km	≤ 5 km
LTS 1	3.66%	1.60%	0.86%	0.35%
LTS 2	18.78%	9.26%	6.33%	3.12%
LTS 3	56.87%	41.58%	35.79%	31.24%
LTS 4	100.00%	100.00%	100.00%	100.00%

The difference between accessible points of interest and the share of connected, randomly generated trips is relatively equal throughout all level of traffic stress groups (around 10%). Although there is a slightly more substantial decrease for LTS 1 and 2 compared to LTS 3, it is almost negligible. Out of 10 points of interest in a 2 km radius, the level of traffic stress group 2 can only get to one. Not only is this number extremely low, but considering that the majority of adult citizens are part of this group, questions arise about the usefulness of the bicycle network. To explore why the share of connected trips in the accessibility analysis is so different from the one of the connectivity analysis, the origin-destination pairs were investigated. The origin data were just the city's houses, which is one of the two possible reasons for the differences. The trips of the connectivity measure were generated from random nodes in the network, which included, for example, the forest areas with a lot of LTS 1 paths and therefore will have ultimately increased the number of LTS 1 trips in comparison to the accessibility analysis because in the forest there are few to no houses. The second reason was first identified qualitatively by looking at the locations of the points of interest and then confirmed quantitatively. A majority of points of interest are right beside main roads and therefore usually near network segments of LTS 3 and 4. By calculating the path to the closest node of the destination geometry, the point of interest was probably often unreachable for LTS 1 and 2. With the help of QGIS, a short spatial join of the POIs with the nearest network segments' level of traffic stress concluded the following distribution:

Table 5.7: Distribution of levels of traffic stress of the nearest network segment from the points of interest. Note: Percentages may not add up to 100% due to rounding

POI's nearest network segment LTS						
	type of poi					
	total	supermarket	public traffic infrastructure	bank	educational facility	medical facility
LTS 1	**14%**	20%	10%	14%	23%	16%
LTS 2	**14%**	13%	10%	8%	29%	10%
LTS 3	**26%**	29%	25%	34%	27%	26%
LTS 4	**45%**	39%	55%	43%	21%	48%

Confirming the qualitative assessment, only a combined 28% of points of interest are near a network segment that was classified as suitable for low-stress cycling. The fact that 26% of POIs are closest to an LTS 3 network edge and 45% closest to an LTS 4 edge impacts the accessibility of those points of interest drastically. This does not entirely limit a cyclist of lower LTS from getting to this point of interest, as the closest network node was chosen for the accessibility measure, which often has adjacent segments of differing traffic stress levels. However, it limits the paths to that network node and will significantly impact the overall share of connected trips. Notably, LTS 4 has the highest share for all types of points of interest but educational facilities. This analysis, however, cannot answer if this is just an effect of the locations of schools, which tend to lie in the vicinity of living areas, or the deliberate placement of low-stress cycling facilities near those schools.

5.5 District Accessibility Analysis

For the district accessibility analysis, the level of traffic stress 2 was chosen as a baseline, representing the goal of low-stress cycling. For this analysis, the baseline distance was set to 1 km, representing short trips for daily uses that, at the bare minimum, should be possible through the low-stress cycling network like grocery shopping. For every district, 5'000 trips were calculated using the accessibility measure function inside of the district analysis function. The decision to divide the city into districts in this analysis is based on the fact that some neighbourhoods are very small.

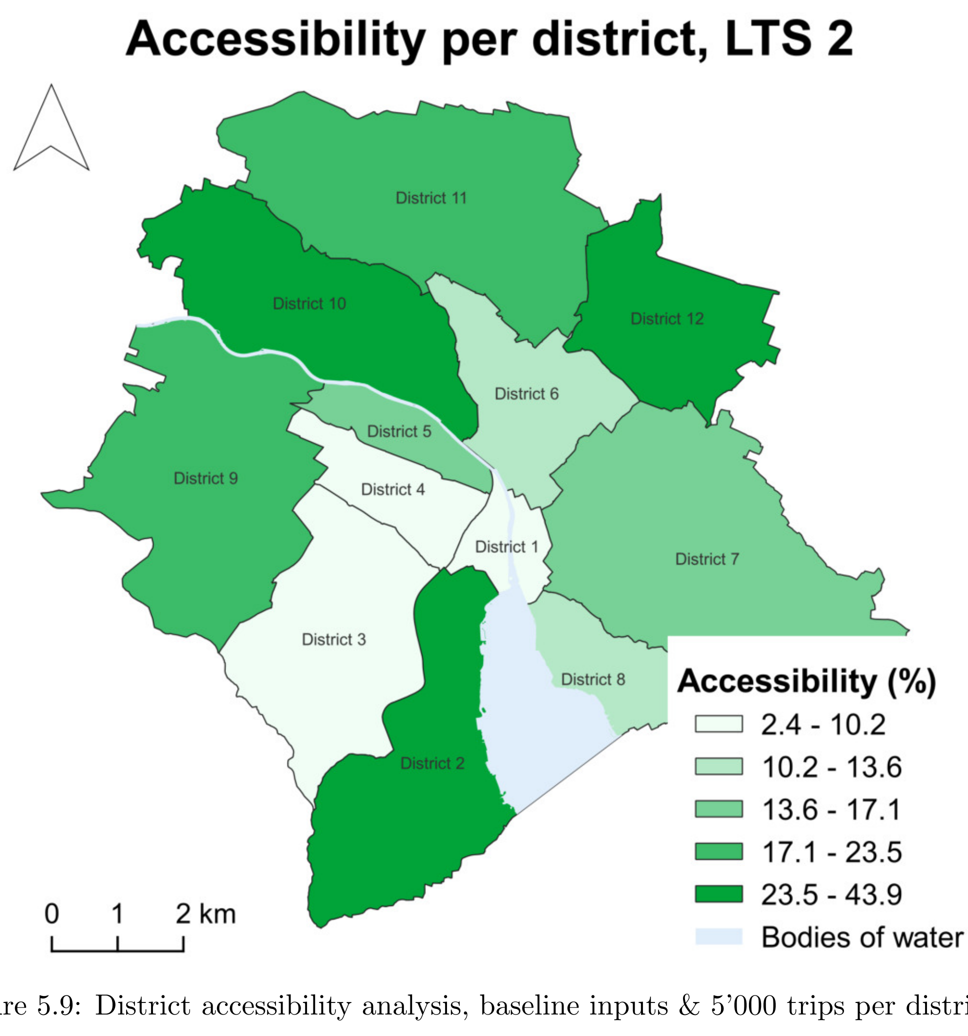

Figure 5.9: District accessibility analysis, baseline inputs & 5'000 trips per district

Therefore, the results would be hard to interpret and compare because few roads would be very impactful on its analysis, and it would have significant consequences if they were classified wrongly due to the matching process. Although bicycle users do not care about the borders of these districts while cycling, an overview and possible policy recommendations can be based on this analysis.

The low-stress bicycle network supplies the houses of Zurich with accessibility to points of interest between 2.40% for district 1 and 43.94% for district 12. Apart from districts 2 and 3, the accessibility of all districts lies in a closer range of 10 to 25%. Although a general assessment of the quality of the low-stress network can be made from this analysis for the districts, it is unclear where the low accessibility stems from, considering the previous analysis of the traffic stress levels near the points of interest. However, by running the same analysis for every POI type, some possible explanations can be established.

Table 5.8: District comparison of accessibility per point of interest type, LTS 2 network, trip lengths = 1km

Accessibility per poi type per district, LTS 2						
	type of poi					
district	**total**	supermarket	public transport	bank	educational facility	medical facility
1	**2.40%**	2.63%	2.28%	2.79%	3.08%	1.85%
2	**27.82%**	27.79%	25.46%	21.68%	32.51%	27.61%
3	**10.06%**	6.20%	10.55%	6.41%	9.37%	8.49%
4	**5.63%**	7.36%	5.18%	1.12%	8.76%	5.30%
5	**15.64%**	23.43%	11.60%	1.36%	21.94%	12.62%
6	**12.23%**	12.10%	11.25%	0.86%	18.18%	10.28%
7	**16.10%**	11.96%	14.55%	6.48%	16.99%	13.00%
8	**10.86%**	6.29%	10.75%	0.48%	16.72%	4.74%
9	**17.70%**	21.75%	16.10%	9.65%	19.19%	13.32%
10	**23.75%**	24.78%	21.67%	11.35%	29.40%	18.77%
11	**22.73%**	20.19%	20.93%	2.50%	29.09%	16.71%
12	**43.94%**	39.28%	44.93%	48.32%	47.84%	49.82%

In the districts where the accessibility is equally low for all types of points of interest, two possible sources could be responsible. Either a majority of the network segments are classified as LTS 3 or 4, or there is an obvious problem with the network structure, for example missing links. Either way, the points of interest are not the deciding factor.

This, in turn, is also valid for districts with high accessibility throughout all types of POIs, just reversed with a majority of network segments classified LTS 1 or 2 and a fine-grained network structure. Upon a closer look at districts 1 and 12, which have the lowest and highest accessibility, it looks to be part of both (figure 5.10). District 1 has three problems that lead to low accessibility. First, a substantial amount of network segments were assigned LTS 3 or 4. Second, the amount of roads in the middle of the district seems low in the data. Although there are many roads on which it is prohibited to cycle, some of those bans were lifted in the meantime. This means that the amount of low-stress roads to bypass the high-stress roads is significantly lower. Third, due to the river 'Limmat', there is a lot of pressure on the crossing links, which can make a lot of destinations inaccessible based on the LTS of the links or the adjacent edges. District 12, on the other hand, has a lot more network edges classified LTS 1 and 2 and often has low-stress crossing options over bigger roads with high levels of traffic stress.

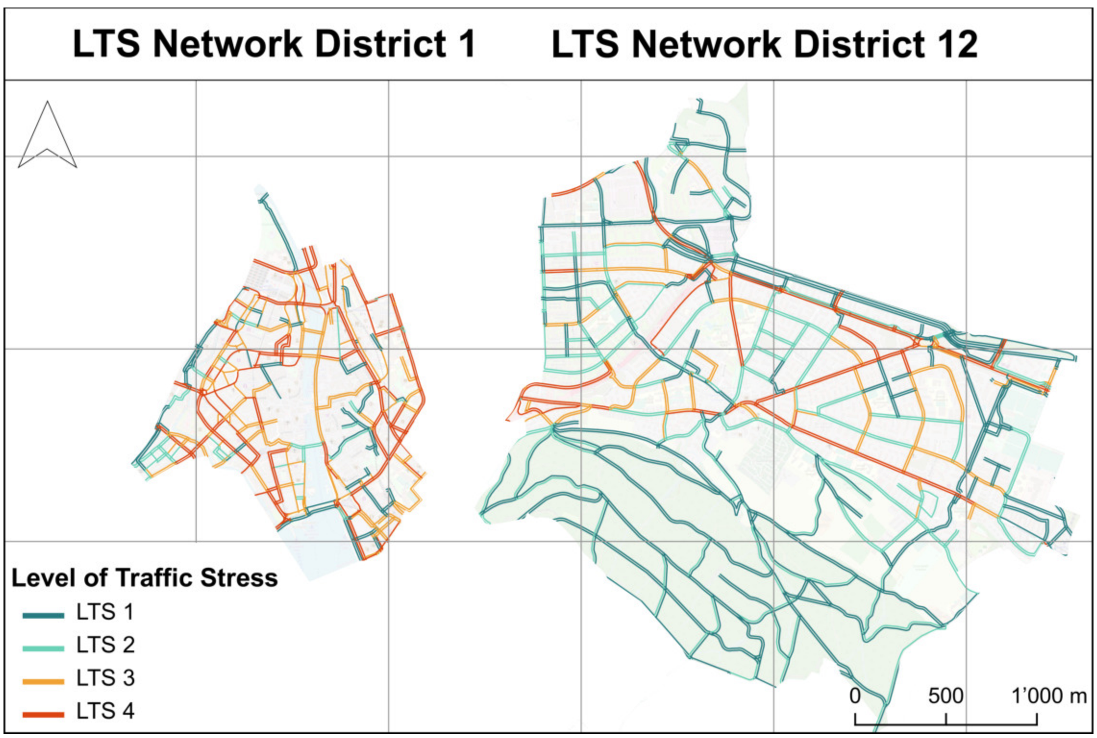

Figure 5.10: Comparison of the level of traffic stress networks of districts 1 and 12.

For districts of strongly varying accessibilities for different points of interest, the points themselves seem to be the problem. For district 11, the accessibilities are relatively similar, but for one strong outlier, the banks with only 2.5% accessibility. Either there are very few to no banks in this district and therefore longer, more stress-prone trips must be cycled, or they are surrounded by high-stress roads, preventing the LTS group 2 from accessing them. The reverse can also be observed for a few districts, where the accessibility to educational facilities is very high compared to the other POIs. As mentioned before, this could be due to the locations of the educational facilities or due to well-developed bicycle facilities around them. The reverse statement of 'where there are many POIs of a certain type, the accessibility is automatically going up' is not true because it is still based on the LTS network. In district 1, for example, there are 30 banks in the very small district, but accessibility to banks is not especially high compared to the other points of interest due to its bottleneck, the level of traffic stress.

5.6 Planned Bicycle Network

Two potential instances of that network were created for the analysis of the planned bicycle network, both of which resemble a future ambition of the city's bicycle planning plan. As introduced in the methodology part of the thesis, the first version will only focus on the fast routes of the planned network, while the second version will additionally include the base network as necessary to be LTS 1. From now on, they will be called version 1 and version 2 for simplicity's sake.

Table 5.9: Connectivity per trip length of the two versions of the planned networks

Connectivity Planned Networks								
	trip lengths							
	fast routes = LTS 1				fast routes = LTS 1, base network = LTS 1			
	≤ 1 km	≤ 2 km	≤ 3 km	≤ 5 km	≤ 1 km	≤ 2 km	≤ 3 km	≤ 5 km
LTS 1	26.70%	18.01%	13.83%	11.10%	49.63%	43.68%	42.34%	44.03%
LTS 2	44.53%	34.93%	30.70%	28.16%	65.73%	59.96%	58.80%	62.02%
LTS 3	74.48%	68.76%	67.11%	69.64%	82.10%	77.23%	77.09%	78.77%
LTS 4	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%

Both versions have an overall much higher connectivity than the current network. Version 2 obviously includes many more network edges defined as LTS 1 and therefore also has an overall higher connectivity throughout all level of traffic stress groups and distances compared to version 1. However, there are a few interesting dynamics to be seen in table 5.9. The first one is that for version 1, although the decrease of connectivity with greater trip lengths is similar to the current network, for the traffic stress level 3, there is only a slight decrease of connectivity, which even goes up between ≤3km and ≤5km. A possible explanation for that is that the main burden of the LTS group 3 is the large amounts of technically connected trips that are however unsuitable due to excessive detours. With the bicycle fast routes, a more direct low-stress network for longer trips is created, which for example allows for longer detours to prevent high-stress roads after arriving in the targeted district.

The second interesting dynamic is that a similar effect can be observed for version 2 with the additional base network classified as LTS 1. This time however, the effect is replicated for not only LTS 3 but also for the two low-stress groups LTS 1 and 2. Besides the immense absolute increase in connectivity (26.70% to 49.63% for ≤1km trips), there is only a minimal decrease up to ≤3km (42.34%) and the same small increase for trips ≤5km (44.03%). This stability of the connectivity throughout the different trip lengths can be attributed to an instance of a low-stress cycling network that does not have low-stress connectivity islands and high-stress borders that limit cyclists of LTS tolerance 1 and 2 to travel longer distances. The last dynamic is that for the level of traffic stress 3, the inclusion of the base network did only have a minimal impact, less than 10% difference throughout all trip lengths. Although the group has very high connectivity overall with around 70-80%, the limiting factor seems to be solely the roads with assigned levels of traffic stress 4. A more granular low-stress network, like the improvement of the base network, does not seem to benefit them significantly.

Notably, the level of traffic stress group 2 has the overall highest increase in connectivity of all groups in version 2 of the modeled network. From an increase of 34.92% for ≤1km trips (30.81% to 65.73%) to a staggering 54.30% increase for trip lengths ≤5km (7.72% to 62.02%). This shows an overlap of benefits for both low-stress groups, which are the main targets of a successful and inclusive bicycle network. Variation 1, on the other hand, increases benefits for all groups for shorter trips, is however unsustainable for longer trips, where it clearly favors the LTS group 3.

Table 5.10: Accessibility per trip length of the two version of the planned networks

	Accessibility Planned Networks							
	trip lengths							
	fast routes = LTS 1				fast routes = LTS 1, base network = LTS 1			
	≤ 1 km	≤ 2 km	≤ 3 km	≤ 5 km	≤ 1 km	≤ 2 km	≤ 3 km	≤ 5 km
LTS 1	14.05%	10.57%	8.04%	6.05%	40.43%	36.36%	35.11%	35.94%
LTS 2	31.92%	25.65%	23.12%	22.12%	55.91%	51.58%	50.57%	54.33%
LTS 3	67.84%	62.31%	62.43%	65.16%	77.42%	73.12%	73.55%	76.06%
LTS 4	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%

The accessibility of the planned networks mostly follows the just discussed connectivity. While version 1 increases the accessibility of all groups for shorter trips evenly by around 10%, accessibility on longer trips is disproportionately higher for LTS 3 compared to LTS 1 and 2. For trips of ≤5km length, the 30.89% difference between LTS 1 and 3 (0.35% / 31.24%) of the current network rises up to 59.11% (6.05% / 65.16%). Although the relative increase is much higher for LTS 1, the absolute increase in this case is so overwhelming in perspective that the increase for LTS 1 is almost negligible. Version 2 follows the same trends as the connectivity results, as LTS 1 and 2 experience not only a strong increase in absolute accessibility but also gain stability in the networks in terms of deviation of accessibility due to differing trip lengths. Again, the highest increase in accessibility is calculated for the level of traffic stress group 2 with an increase of up to 51.21% for trips of ≤5km length.

The last part of the planned network analysis is the district accessibility analysis. For the two planned network versions, the accessibility per district was calculated for the LTS network 2 with 5000 iterations per district and a distance of 1km. The results in table 5.11 are sorted by the highest increase of accessibility from the current network to version 1 of the planned network to visualise, which districts are more and which are less affected by the bicycle fast routes.

Table 5.11: Accessibility per district of the planned networks, LTS 2, trip lengths = 1km. Note: Numbers in brackets represent difference to accessibility of current situation (first column)

Accessibility per district, comparison planned networks, LTS 2			
district	current network	fast routes = LTS 1	fast routes = LTS 1 base network = LTS 1
4	5.63%	27.32% (+21.69)	57.55% (+51.92)
12	43.94%	64.43% (+20.49)	75.26% (+31.32)
5	15.64%	35.76% (+20.12)	58.11% (+42.47)
9	17.70%	35.75% (+18.05)	64.09% (+46.39)
2	27.82%	43.59% (+15.77)	78.33% (+50.51)
11	22.73%	37.30% (+14.57)	56.93% (+34.20)
10	23.75%	38.27% (+14.52)	56.05% (+32.30)
6	12.23%	25.98% (+13.75)	48.20% (+35.97)
3	10.06%	22.94% (+12.88)	47.77% (+37.71)
8	10.86%	19.33% (+8.47)	54.89% (+44.03)
7	16.10%	23.91% (+7.81)	45.40% (+29.30)
1	2.40%	9.97% (+7.57)	28.80% (+26.40)

District 1 is calculated to have the lowest increase in accessibility of all districts (+7.57%), whereas district 4 should experience the most significant increase in accessibility (+21.69%) due to the planned fast routes. Interestingly, these two districts are the two districts with the lowest accessibility in the current network. As both districts are planned to receive relatively equal parts of fast routes, this leads to believe that some of the bicycle network's structural problems will be fixed by the locations of the fast routes in district 4 but not in district 1. District 12, with the leading accessibility in the current network is additionally the district with the second most increased accessibility in version 1 to a total of 64.43%.

By comparing the results of version 1 to version 2 of the planned networks, some assessments about the structure of the district's network can be made. High differences in accessibility between version 1 and version 2 can be a sign of a potential lack of a fine-grained structure of the bicycle network, which can be filled with the inclusion of the planned base network. For district 12, the accessibility only increases by another 10.83% between version 1 and version 2, as its current basic structure is relatively stress-free, as also shown by its high current accessibility. District 4 experiences another big increase of 30.23% between versions 1 and 2, showing the need for a base network.

In comparison to version 1, district 1 also has a significant increase in accessibility in version 2, suggesting that the problem of the district lies in the fine-grained structure of the network and will not be solved by the planned bicycle fast routes. The two districts with the most considerable increase in accessibility between both versions of the planned networks are district 8 and 2 (35.56% / 34.74%).

6 Discussion

This thesis analysed the bicycle network of the city of Zurich regarding its imposed levels of traffic stress. First, this discussion section will review the developed LTS networks in regard to existing studies while also comparing them to data sets from Zurich that can provide information about their validity. Second, for the first research question, the connectivity and accessibility results will be analysed in the context of 'leave no one behind'. Third, the second research question will be answered by critically reflecting on the results of the planned network exploration part of the thesis. Fourth, building on the second research question, planning recommendations as well as data recommendations will be brought forth based on the results of the planned network exploration. Finally, this section will describe the work's limitations and shortcomings. Throughout the discussion section, the main takeaways will be presented.

6.1 LTS Network

The evaluation of the level of traffic stress in the bicycle network of the city of Zurich has revealed valuable insights into the different experiences of its cycling citizens. The four LTS groups 1-4 of varying traffic stress tolerances were assigned a respective network, revealing drastic differences in network quality between the groups. The classification of the network segments, strongly influenced by the many times revised classification schemes of Peter Furth (2022), was tailored to the specifics of Zurich. Not only did that mean compromising for some standard variables like road composition (Mekuria et al., 2012; Winters et al., 2016) due to a lack of data, but it also included expanding the set of variables to fill the need of including important factors of local road situations. The road slope was introduced as a factor discussed for its potential influence on traffic stress (Mekuria et al., 2012) and was proven relevant in route choice of cyclists in Zurich (Menghini et al., 2010). The two additional variables of tram tracks and pedestrian islands were introduced as important variables due to being well-known safety hazards in the city of Zurich (Biland, 2023). With the help of the civil engineering office of Zurich and Pro Velo Zürich, the classification was expanded to not only make the analysis more realistic to Zurich but also to explore the research's gap of including specific local road situations that are known to impact the comfort levels as well as safety levels of cyclists.

A total of 61.2% of network segments were classified as suitable for low-stress cycling (LTS 1: 38.35%, LTS 2: 22.85%), similar to a 67% in San Jose, California (Mekuria et al., 2012). Although this number is relatively high, the respective available networks of the level of traffic groups 1 (figure 5.3) and 2 (figure 5.4) consist out of very cut up and disconnected parts, presenting a network, that fails to meet the basic design principle *cohesion* of a bicycle network (CROW, 2007). One reason for the discrepancy between the visual network and the high number of low-stress network segments is the three forest areas in Zurich with almost exclusively low-stress paths. In contrast to San Jose, California (Mekuria et al., 2012) and Atlanta, Georgia (Bearn et al., 2018), the low-stress network of Zurich is comprised of much more 1-5 road segment parts instead of smaller neighbourhoods with equal levels of traffic stress. The typical grid layouted roads of the USA lead to a relatively clear differentiation of low-stress and high-stress roads, whereas in Zurich, low-stress sections are found in different shapes but also crossed more unpredictably by bigger, high-stress roads. A road network whose high-stress roads are not as regular and not as strictly splitting low-stress neighbourhoods with up to 6 lanes roads, there is also a potential to circumvent the high-stress barriers more effectively. Due to not being cut off by different large main roads in all directions, more pronounced low-stress alternatives for the high-stress main roads would be possible and would alleviate finding a suitable low-stress crossing intersection. However, this possible strength of Zurich's road structures does not seem to be employed in the current bicycle network.

A relatively high number of one-way and contraflow roads, especially on residential roads, further split up the low-stress network islands. This focus on the networks bidirectionally was not only important for accounting for these one-way and contraflow roads but was also crucial for the added slope variable to isolate the edges with an upward slope, as a negative slope does not increase the level of traffic stress. While the assumption of bicycle trips usually being round trips with the same outward and return route would eliminate the need for this bidirectionality regarding slope (Mekuria et al., 2012), it would also leave out the intricacies of the bicycle network. In Zurich, in addition to the one-way and contraflow roads, many roads have different cycling infrastructure in their two directions, resulting in different traffic stress levels. With a unidirectional approach, these segments would be assigned the higher level of traffic stress, leaving out the possibility of using those low-stress parts of the roads as a part of a trip while returning on a different low-stress network segment.

For a rough assessment of the quality of the modeled LTS network, it was compared to two additional data sets. 'Bikeable.ch', a website that allows Zurich's citizens to enter problematic cycling spots, serves as a proxy of the cycling citizens' perceptions. In contrast, bicycle accident data of Zurich can shine a light on the problematic areas of the city. Of bikeable.ch's negatively rated entries, 28% lie next to a LTS 3 network segment, and 42% lie next to a LTS 4 segment, suggesting a correlation of increased classified LTS level of this thesis to badly perceived cycling spots. From the 5991 recorded bicycle accidents of the data set from 2011 to 2021, 30% of accidents lie next to an LTS 3 segment, whereas 42% of accidents lie next to an LTS 4 segment. Notably, some of the traffic stress levels of the network edges will have changed over the years, meaning that certain 'bikeable.ch' entries and accidents were recorded on the segments in different conditions. Although the comparison to these two data sets does not suffice as a conclusive validation, it provides a crucial indication of the method's validity in this study.

Main Takeaways

- Important local variables were able to be added to the level of traffic stress methodology for a more realistic case study.
- Apart from Zurich's forest areas, the low-stress cycling network consist out of mostly cut up sections of roads and paths.
- A comparison to cyclists' perceptions and bicycle accident data indicates the potential of the LTS methodology in Zurich.

6.2 Low-stress Connectivity & Accessibility

Research Question 1: Are specific groups of citizens excluded from bicycle transportation in the city of Zurich due to a lack of connectivity and accessibility in the bicycle network based on their level of traffic stress tolerance?

While the different levels of traffic stress networks give a visual impression of the quality of the respective networks, connectivity and accessibility analyses assess them more quantitatively. For the level of traffic stress methodology based on the weakest link principle, these measures do not assess the quality of the overall structure of the network but rather give information about the quality of the networks for the different level of traffic stress groups. Trip generations based on Mekuria et al.'s research (2012) with different trip lengths for each LTS group reveal drastic differences in connectivity throughout all groups. Notably, while comparing the results of the upcoming connectivity and accessibility analyses with the results of previous research, the differences in the LTS classifications must be kept in mind. Due to the more localised and more realistic approach of the LTS classification, a comparative quality of the methodology is lost. In turn, an additional comparative quality within this work's results is achieved and will be a focal point of the remaining discussion.

With the baseline classification and the trip length of an average bicycle trip in Europe of 3km (European Commision, 2023), a connectivity of just 3.88% for LTS 1 and 13.69% for LTS 2 was calculated. A connectivity of around 1 out of every 8 trips for LTS 2 and 1 out of 25 trips for LTS 1 confirms the visual impression of an essentially unusable bicycle network for these two user groups. Almost equal results were observed in San Jose, California with a LTS 2 connectivity of 7.7% (Winters et al., 2016) for trips ≤4miles, which is similar to this works ≤5km category with a connectivity of 7.72%. However, the connectivity for trips below 4 miles were not calculated (Mekuria et al., 2012; Winters et al., 2016), missing out on important intricacies of shorter trips, especially for the two low-stress cycling groups, which this work was able to provide for Zurich. For a trip length of ≤1km, a connectivity of 14.5% for LTS 1 and 30.81% for LTS 2 was calculated. Although clearly better than the connectivity for trip length ≤3km and ≤5km, for trips that would for example be to a friend's house or a supermarket, which would most likely be close by in the neighbourhood, these numbers are still very low.

The accessibility of the respective LTS networks assesses these more specific, applied versions of trips. With specific origin-destination pairs from Zurich's houses to points of interest equally important to all citizens, this work combined similar LTS literature (Mekuria et al., 2012; Kent and Karner, 2018). For LTS groups 1-3, the accessibility to these points of interest is lower than the general connectivity due to more specific destinations, which tend to lie on main roads with high levels of traffic stress. The '20 minute neighbourhood', a concept of accessibility widely used in spatial planning, suggests that in a modern city, daily needs should be accessible within 20 minutes of travel by any mode of transportation (Capasso Da Silva et al., 2019). Alongside Moreno et al.'s (2021) '15 minute city' and McNeil's (2011) '20 minute neighbourhood bikeability', the civil engineering office also brings the concept more specifically into bicycle transportation and suggests that daily accessibility within 10/15 minutes, by bicycle or also by walking is a goal of Zurich. With a proposed 16 km/h as an average cycling speed (Raustorp and Koglin, 2019), this would result in a functional distance of 2.7 - 4km, which is similar to McNeil's (2011) functional distance definition of 1 to 2.5 miles. This might be realistic in a world of a homogeneous cycling group with no safety and comfort concerns, but is far from realistic in the current bicycle network of Zurich. With an accessibility of 9.26% for LTS 2 for trips with length ≤ 2km and 6.33% for ≤3km, the current 10/15 minute cycling concept is only realistic for less than 1 out of 10 people with low traffic stress tolerance.

Circling back to the first research question of this work, with these results of connectivity and accessibility of LTS groups 1 and 2, some citizens are definitely left behind. However, while 'Leave no one behind' often regards a minority of people left behind, in this case, they are the biggest group of citizens left behind. The original 'interested but concerned' group of cyclists, which is the equivalent of the LTS 1 and 2 groups was surveyed to be 51-56% (Dill and McNeil, 2016) of all citizens, of which 9 out of 10 are currently left behind regarding the accessibility goal to reach daily points of interests within 10/15 minutes of cycling. A lack of accessibility to daily points of interest inevitably limits using the bicycle for those LTS groups to be recreational instead of a valid mode of transportation (Hanson and Hanson, 1976). Apart from short trips inside the realm of the '15 minute city', daily longer trips, mainly from citizens' homes to work, are vital for the bicycle's success as a valid mode of transportation. However, these trips are even less realistic for LTS groups 1 and 2 (primarily relevant for LTS 2) as connectivity and accessibility decline drastically with increasing trip length. These barriers of LTS groups 1 and 2 can explain the high rates of non-drivers (39%) and occasional drivers (34%), which need improvement in order to use their bicycles on a more regular and daily basis. The principle of urban planning to fairly distribute a cities space (Gössling et al., 2016) seemingly is not able to be met regarding the distribution of Zurich's cyclist groups. Although these numbers provide crucial insight into the state of the current situation of the bicycle network, the planned future network analysis of the city is essential to assess whether the planned efforts will improve the situation for LTS groups 1 and 2 or if they reproduce an unintentional exclusion of a big part of citizens.

Main Takeaways

- Very low rates of connectivity and accessibility for LTS groups 1 and 2 largely exclude them from using the bicycle as a valid mode of transportation in Zurich.
- If the vision of a 15 minute city wants to be achieved, low-stress accessibility to daily points of interest needs to be drastically improved.
- By ignoring the needs of LTS groups 1 and 2, not only a small group of people but a majority of citizens is left behind.

6.3 Planned Network Exploration

Research Question 2: How do the future efforts of the city to improve bicycle transportation affect network connectivity and accessibility, and are they equitable for all types of cyclists?

With the 'Velostrategie 2030', Zurich defined the future of bicycle transportation in the city. A new network structure, based on the three categories *fast routes*, *main network*, and *base network*, is planned to lay the foundation of bicycle transportation that suits all kinds of cyclists in their own respective ways. This proposed network structure is this thesis' focal point of analysis and therefore excludes most of the remaining 'Velostrategie 2030'. Any conclusion or critique of the remaining discussion is therefore specifically for this section of the planning strategies and is based on the structure of the proposed planned network, its description, and goals in the 'Velostrategie 2030', the discussions with both the civil engineering office and Pro Velo Zurich and the results of this thesis. This work does not attempt to critique the bicycle planning strategies of the city in its entirety.

For version 1 of the modeled planned network with the fast routes assigned to be suitable for all cyclists and therefore suitable for LTS 1, important dynamics were detected (figure 5.9). For LTS 1, the connectivity increased about 10% in comparison to the current connectivity, roughly doubling them for all trip lengths. While this increase is significant, the absolute connectivity is still very low, with under 14%, especially for trips over 2km. For the level of traffic stress group 2, the construction of the planned fast routes will mean a significant improvement overall, but especially for longer trips, almost quadrupling for trips $\leq$5km. However, with the low rates of connectivity in the current bicycle network, the relative increase has to be analysed carefully as the almost quadrupling of connectivity in reality means just an increase from almost 1 out of 10 successful trips to just under 3 out of 10 successful trips, still leaving 7 out of 10 people of this LTS group behind. The most significant, and for the evaluation of the fast routes essential increase in connectivity experienced the level of traffic stress group 3, especially for long trips, where connectivity is even higher than for medium length trips (figure 5.9). These dynamics are identical to the accessibility analysis of version 1. The connectivity for LTS 3 increased the most with a sum of 92.26% increase throghout all trip lengths, while LTS 2 increased with a sum of 65.32% and LTS 1 with 32.24%.

According to these results, the ideal construction of the planned fast routes will therefore, in regards to accessibility, benefit the level of traffic stress group 3 three times as much as it does the LTS group 1 and twice as much as the LTS group 2. These differences are not as drastic for general network connectivity, once again pointing to the problem of common high-stress locations of the points of interest. These differences raise important questions about the use of the fast routes for the specific LTS groups. For LTS 3, the fast routes will present new, fast and more importantly, direct routes to different districts and ultimately, good alternatives to the existing main roads with traffic stress level 4. Long trips will be more direct for them and will therefore also provide more leeway for shorter detours before or after the fast route part of their trips, clearly raising the connectivity and accessibility as observed in figure 5.9 and 5.10. For LTS groups 1 and 2, the network of the fast routes represents the first, in itself connected network, that is constructed to suit their needs of comfort and safety. The problem, which can be reflected in the still relatively low connectivity and accessibility, is that the fast routes only connect the different districts and need a more fine-grained supporting network to connect realistic start and endpoints of bicycle trips. In the proposed bicycle network of the city, the base network is supposed to fulfill this purpose.

The therefore vital assessment of the planned base network was approximated with version 2 of the planned network, additionally including the ideal base network as LTS 1. In this version, both the connectivity and accessibility of LTS 1 and 2 rise drastically and, just as meaningfully, stay the same throughout all trip lengths. This indicates that by including the base network, the planned network would form a functioning network for all types of cycling trips, this time also for LTS groups 1 and 2. The only minimal increase in connectivity and accessibility of LTS 3, on the other hand shows that their perceived network was relatively similar as in version 1. Interestingly, the percentages of unconnected trips due to excessive detours were relatively equal for all LTS groups in contrast to the current situation, where this measure was very high for LTS 3 and very low for LTS 1 and 2. This suggests that the around 20/25% unconnected trips are due to road segments with a traffic stress level 4, equally forcing all the other groups to excessive amounts of detour. The district accessibility analysis of the different planned networks provide additional valuable insights into the distribution and potentials of different districts, suggesting problem areas of the planned networks. This analysis suggests, that in order to meet one of the main goals of the 'Velostrategie 2030', "the creation of a direct, continuous and safe network, that is attractive to 'habitual drivers' and 'occasional drivers' to increase their share" (Stadt Zürich, 2021, p. 7), the planned base network needs to be reassessed for the quality of its intended use.

Main Takeaways

- The fast routes of the planned network, if implemented as planned to be suitable for LTS group 1, will have a big impact on the cycling network of Zurich. However, without including the base network as a supporting network for LTS groups 1 and 2, the fast routes fail to provide adequate connectivity and accessibility for those groups and rather provide a significant improvement for LTS group 3.
- Although the planned fast routes are planned to be suitable for LTS 1, and an accusation of not including this target group them would be inappropriate, the resulting effects do not benefit LTS groups 1 and 2 enough without an adequate base network.
- With a low-stress requirement for the base network, the planned network provides reasonable rates of connectivity and accessibility for all level of traffic stress groups.

6.4 Planning & Policy Recommendations

Although the calculated values of connectivity and accessibility can not be taken at face value due to limitations discussed in the next section, the dynamics and differences of the calculations give crucial insight into what needs to be considered moving forward in bicycle transportation planning in Zurich.

Cyclists with low traffic stress tolerances need special attention: Bicycle users are a diverse group with different needs exacerbated by their vulnerability on the road. Planning a bicycle network for everyone, as the 'Velostrategie 2030' and the civil engineering office suggest, generalizes the very specific problems of the user groups LTS 1 and 2, the equivalent of occasional drivers and a part of non-drivers in Zurich's way of differentiation. Cycling facility improvements that do not provide low-stress cycling opportunities benefit just a small part of citizens, generally those not needing further improvements. Stuart and Samman's (Stuart and Samman, 2017, p.1) description of 'Leave now one behind', the need of explicit and pro-active attempts to ensure populations at risk of being left behind are included from the start, is vital for the future of bicycle transportation planning in Zurich. In theory, all improvements are positive in the overall realm of bicycle planning as they often improve bicycle safety for the already cycling population and make a small contribution to the overall acceptance of bicycles in the city. However, in a situation in which more than half of the citizens are excluded from riding a bicycle due to their traffic stress tolerance, priorities need to be reconsidered. Minor improvements for the benefit of the already cycling population miss the vital goal of the 'Velostrategie 2030' regarding reaching target groups, who currently only rarely or never use their bicycles. The critique of the lowest hanging fruit of the 'Leave no one behind' principle bears some resemblance to the large number of small bicycle transportation improvements in the last years, fighting for the right cause but missing the main goal. This work has shown that an improvement and focus on the LTS 1 group brings equal, if not sometimes even better improvements for LTS groups 2 and 3, providing not only an equitable planning approach but also a productive one.

The base network of the planned network needs to be assessed in more depth: The definition of the new planned network structure consisting out the *fast routes*, *main network* and *base network* does not automatically make these roads suitable for the respective intended uses. While for the fast routes, an active effort is made to reach a standard of LTS 1 suitability, the base network does not have any standards of being suitable for the LTS 1 group, resulting in problematic usability assumptions. This passive planning approach for the base network is insufficient for the two low-stress cycling groups as they rely on a functioning network of connected roads and paths within the respective traffic stress levels. The base network with the LTS classification of this work consists of 24% network edges with assigned level of traffic stress 3 and 15% assigned LTS 4. This means that a total of 39% network edges of the base network are not suitable for LTS 1 and 2 and therefore not satisfactory for their intended use of providing low-stress extensions of the planned fast routes. Version 2 of the modeled planned networks confirms that the passive planning approach needs to be reevaluated for the success of low-stress connectivity and accessibility. It further shows the big potential of the planned network with the inclusion of an active planning strategy of the base network.

Zurich's bicycle data policies need to be updated: As this work has shown, the bicycle network assessment is an invaluable tool for bicycle transportation planning. With the current data availability, this was however only barely achievable and resulted in clear limitations in regards to specific result values. A data set on bicycle intersection infrastructure and a regularly updated bicycle path and lane data set is a trivial improvement that should be high on the list of priorities for the city. Additional attributes like bicycle lane width or road composition would also be essential for a more in-depth infrastructure analysis. To the author's knowledge, a clearly defined road network with unique identifiers per segment does not exist, which would also greatly simplify and improve the process of road matching in bicycle network analyses. The importance of data quality can not be overstated for a methodology like this, where many different results are generated from the same ground network.

6.5 Limitations

The limitations of this work can be categorized into three categories: data-related limitations, methodology-related limitations, and validation-related limitations. As previously mentioned, data-related limitations of this work mainly stem from the unavailability of crucial bicycle data. While replacing and adapting data does not automatically decrease the validity of the results, it does stray away from the revised and accepted literature of the study field and decreases the ability to compare results. The impacts of data quality can be felt throughout the whole thesis process. For example, in this work, many additional results could have been generated from the Jupyter Notebook with its adaptive structure. However, at this point in time, the underlying data needs improvement as the different results reproduce the same problems stemming from the data. Differing line geometries for example lead to another significant limitation that partly is due to irregular data sets, but also partly due to the methods of matching those geometries. While the simple matching approach was sufficient for this work, a more dedicated and in-depth matching algorithm would increase the quality of the LTS classification and the thereon-based network analyses. Another methodology-related limitation of this work was the overall loss in the comparability of the results to other similar studies due to the more localised version of the LTS classification. A last big limitation of this work is that due to the scope of this thesis, originally planned validations with the use of 'crowdsourcing' (Krykewycz et al., 2011) were not possible, exposing a need for the validation of the developed LTS classification. These limitations conclude, that the results of the network analyses can not be taken at face value until the before-mentioned limitations are addressed and are currently limited to their comparative quality and their insight on Zurich's planned bicycle network.

7 Conclusion

This thesis attempted to assess the imposed levels of traffic stress (LTS) on cycling citizens in the bicycle network of the city of Zurich. Due to variations in perceived safety and comfort, four groups of differing traffic stress levels were analysed in the context of their own suitable networks, in which they do not have to exceed their tolerable traffic stress levels. The mainly from the United States originating bicycle network classifications into the four levels of traffic stress were successfully adapted to suit Zurich's local intricacies. Differences to recognised level of traffic stress classification schemes stem from a lack of data availability and from this works goal to additionally include important local variables like slope, tram tracks, and pedestrian islands. The classified bicycle network was then analysed regarding connectivity and accessibility to public services for each individual LTS group, revealing severe deficiencies for the two low-stress cycling groups LTS 1 and 2.

An additional analysis of two versions of the planned bicycle network of the city of Zurich provided insights into the origins of the low connectivity and accessibility and further revealed possible problems and shortcomings of the planned network. Due to an open implementation of the network analyses, specific scenarios and questions could be explored, for example, regarding different trip lengths or to investigate spatial variations of administrative divisions like districts. The results of the planned network exploration provided crucial information about the problems of the planned network regarding low-stress connectivity and accessibility.

This work gave insightful and realistic planning and policy suggestions for a successful and equitable bicycle network for the city of Zurich to leave no one behind in the future. While dealing with case-specific limitations of data availability, this thesis was able to show the successful adaptation and implementation of a recognised methodology to suit the local intricacies of a modern city.

7.1 Future Work

Based on this thesis, future work could move in different directions. One direction would be to delve even further into the local conditions of the city of Zurich and improve the analysis to be even more realistic. Besides improving the before-mentioned lack of bicycle data, the best way to achieve that would be to validate this work's results. These validations would be necessary at the stage of LTS classification to ensure that the assigned levels of traffic stress align with cyclists' perceptions. Additionally, at the stage of connectivity and accessibility, it would be crucial to find out which of the modeled connected, respectively deemed unconnected trips would, in reality, be cycled by which level of traffic stress groups. For further insights into the efforts of the city of Zurich to improve bicycle transportation, more specific scenarios and projects could be modeled to assess their impact on connectivity and accessibility, but also their equitability between different types of cyclists.

Moving into a more generalised direction, a similar tool to the one of this thesis could be created for reproducing the ability to easily include local variables into the widely recognised level of traffic stress methodology. With a more widely usable tool like this, further improvements in regards to the analysis of planned bicycle infrastructure could be made, simplifying for example the process of assessing planned infrastructure or even generating possible solutions for revealed problem areas.

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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

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