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ADDRESSING LARGE CHALLENGES WITH SMALL INFRASTRUCTURE: ENVISIONING THE E-BIKE CITY

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Abstract

Well-functioning transportation is essential for robust economies, social mobility, and personal freedom. However, making travel faster and easier by expanding highways, tunnels, and bridges is reaching its limits. Large transport infrastructure projects in today's complex urban environments are possible only at a rapidly growing cost, and the resulting induced traffic conflicts with a timely de-carbonization of the transport sector. This dilemma hinders effective progress in transport policies.

This dissertation explores a possible paradigm shift, moving from large infrastructure for high maximum speeds toward small and modular interventions prioritizing flexible and space-efficient mobility. It expands on early ideas of an E-Bike City, a proposal to reallocate roughly 50% of urban road space in favor of bicycles and e-bikes while maintaining access for motorized vehicles.

The overarching question addressed in this dissertation is how such a concept would work in the context of Zurich. The underlying research investigates the potential of reallocating road space to cycling infrastructure while respecting the needs of other modes, proposes possible design solutions, and explores the expected impacts on traffic flows and accessibility. The dissertation is structured around four key contributions: (1) theorizing the concept of an E-Bike City, (2) developing a rapid and reproducible process for redesigning transport networks in real cities, (3) proposing detailed street and intersection designs, and (4) evaluating the accessibility and equity impacts of such a transformation.

The first contribution evolves the initial ideas of an E-Bike City into a functional design framework. It defines the guiding principles, challenges, and a research agenda that informs the subsequent contributions. By embedding the concept into a broader discussion on challenges in transport policy and social equity, it establishes a foundation for future work.

The second contribution introduces an automated, reproducible process for rapidly designing possible E-Bike City transport networks. It provides a software package that generates alternative configurations of lanes within the constraints of existing road space while accommodating public transport operations, car access, and on-street parking. The results demonstrate that over 50% of road space can be allocated to cycling infrastructure while preserving high-quality public transport and ensuring access to buildings by car. The resulting network informs the subsequent contributions. The software is published open-source and can be used to envision similar concepts in any city in the world.

The third contribution focuses on detailed street and intersection designs under the E-Bike City concept. It presents a redesign of four intersections in Zurich, together with design norms that can be applied in other, similar cities. Professional visualizations illustrate how an E-Bike City would function in practice, offering a tangible preview of how traffic would work

and how everyday life would feel under the new, ”small infrastructure” paradigm.

The final contribution evaluates the expected impacts of an E-Bike City, using a MATSim simulation and logsum accessibility. The transformation creates a substantial shift from car travel to public transport and cycling and reduces disparities between population groups with the highest and lowest levels of accessibility. However, the analysis also reveals important challenges, including reduced overall accessibility, increased total distance traveled, and detour traffic in some urban neighborhoods.

While these findings reveal important potentials and challenges of the E-Bike City concept, they are subject to three key limitations: The impact assessment assumes no changes in behavior, demography, and land use; the network generation uses multiple simplifications; and the proposed changes are only limited to the transportation network. Further research should show the impacts while considering long-term changes to preferences, housing locations, and shifts in demography. Advances in network design algorithms can deliver networks that provide better overall accessibility, and future studies can also evaluate the E-Bike City in combination with other policy measures like changes to public transport or road pricing.

This dissertation looks into the future, discussing the E-Bike City and ”small infrastructure” as an alternative paradigm in urban transport policy. The findings provide a foundation for future research and policy development, showing that ambitious yet comprehensively planned interventions can create meaningful change in urban transport systems. It answers the overarching question of how such a policy direction would work in Zurich and provides a set of tools for researchers and practitioners for developing it further.

Zusammenfassung

Funktionierende Verkehrssysteme sind essenziell für eine robuste Wirtschaft, starke soziale Mobilität und individuelle Freiheit. Doch ein massiver Ausbau von Autobahnen, Tunneln und Brücken, um das Reisen schneller und einfacher zu machen, stösst zunehmend an seine Grenzen. Grosse Infrastrukturprojekte in dichten urbanen Räumen sind nur noch mit hohen Kosten realisierbar und der dadurch induzierte Verkehr ist im Widerspruch zur schnellen Dekarbonisierung des Transportsektors. Dieses Dilemma behindert eine wirksame Weiterentwicklung der Verkehrssysteme.

Diese Dissertation untersucht einen möglichen Paradigmenwechsel, weg von grossen Infrastrukturprojekten für hohe Maximalgeschwindigkeiten hin zu kleinen, modularen Massnahmen, die eine flexible und raumeffiziente Mobilität priorisieren. Sie baut auf frühen Ideen einer E-Bike City auf, einem Vorschlag, 50% des bestehenden Strassenraums in der Stadt dem Velo- und E-Bike-Verkehr zuzuweisen, während der Zugang zu Gebäuden mit dem motorisierten Individualverkehr (MIV) weiterhin möglich bleibt.

Die übergreifende Frage dieser Arbeit lautet: Wie würde ein solches Konzept in der Region Zürich funktionieren? Die zugrunde liegende Forschung analysiert das Potenzial einer Umverteilung des Strassenraums zugunsten der Veloinfrastruktur, zeigt mögliche Entwürfe für Strassen und Knoten, und evaluiert die erwarteten Auswirkungen auf die Verkehrsströme und Erreichbarkeit. Die Dissertation ist gegliedert nach vier Beiträgen: (1) die theoretische Entwicklung des E-Bike City-Konzepts, (2) die Entwicklung eines schnellen und reproduzierbaren Prozesses zur Neugestaltung von Verkehrsnetzen in realen Städten, (3) die Erarbeitung detaillierter Strassen- und Kreuzungsentwürfe und (4) eine Analyse der Auswirkungen auf die Erreichbarkeit und Gerechtigkeit.

Der erste Beitrag entwickelt die ursprüngliche E-Bike City Idee weiter in ein funktionales Konzept. Es definiert die wichtigsten Prinzipien, Herausforderungen und Forschungsfragen, die den Rest dieser Arbeit prägen. Durch die Verankerung des Konzepts in einer breiteren Diskussion zu verkehrspolitischen Herausforderungen und sozialer Gerechtigkeit schafft es eine solide Grundlage für weitere Arbeiten.

Der zweite Beitrag ist ein automatisierter, reproduzierbarer Prozess, mit dem sich E-Bike City-Verkehrsnetze in bestehenden Städten rasch entwerfen lassen. Es wurde eine Software entwickelt, die alternative Konfigurationen von Fahrspuren innerhalb der bestehenden Strassenräume generiert, während gleichzeitig der öffentliche Verkehr, der MIV-Zugang und die Strassenparkplätze berücksichtigt werden. Die Ergebnisse zeigen, dass Veloinfrastruktur über die Hälfte des Strassenraums einnehmen kann. Dabei wird das heutige Netz des öffentlichen Verkehrs, sowie ein MIV-Zugang zu den Gebäuden aufrechterhalten. Das daraus resultierende Netz ist eine Grundlage für die weiteren Beiträge in dieser Arbeit. Die Software wurde als Open-Source-Tool veröffentlicht und ermöglicht die Entwicklung ähnlicher Konzepte in anderen Städten.

Der dritte Beitrag sind detaillierte Entwürfe von Strassen und Kreuzungen nach Prinzipien der E-Bike City. Gezeigt werden vier Knoten in Zürich, zusammen mit allgemeinen Entwurfsnormen, die auf andere, vergleichbare Städte übertragbar sind. Professionelle Visualisierungen zeigen, wie eine E-Bike City in der Praxis funktionieren könnte und wie sich der Alltag unter diesem neuen Paradigma anfühlen würde.

Der vierte Beitrag untersucht die Auswirkungen einer E-Bike City auf den Verkehr, die Erreichbarkeit und die soziale Gerechtigkeit. Mithilfe von MATSim werden die Verkehrseffekte simuliert und die Auswirkungen werden als logsum-Erreichbarkeit aufgezeigt. Die E-Bike City bewirkt eine deutliche Verlagerung vom Autoverkehr hin zum öffentlichen Verkehr (öV) und Langsamverkehr. Es reduziert auch Differenzen zwischen Gruppen mit der höchsten und der niedrigsten Erreichbarkeit. Gleichzeitig zeigt die Analyse aber auch Herausforderungen, darunter eine reduzierte Gesamterreichbarkeit, eine Zunahme der gesamten Reisedistanz sowie Ausweichverkehr in einigen Quartieren.

Die Ergebnisse zeigen die Potentiale und Herausforderungen der E-Bike City. Sie haben jedoch drei wesentliche Limitationen: Die Bewertung der Auswirkungen basiert auf der Annahme, dass sich das Verhalten, die Demografie und die Flächennutzung nicht verändern; die Netzgenerierung hat mehrere Vereinfachungen; und die analysierten Veränderungen beschränken sich nur auf die Umverteilung des Strassenraums. Zukünftige Forschung sollte untersuchen, wie sich das Konzept unter langfristigen Veränderungen der Präferenzen, der Wohnstandorte und der Bevölkerungsentwicklung auswirkt. Verbesserungen der Netzgenerierung könnten eine bessere Gesamterreichbarkeit produzieren. Darüber hinaus könnten zukünftige Arbeiten die E-Bike City in Kombination mit weiteren Massnahmen untersuchen, wie Strassengebühren oder eine Umgestaltung des öV-Angebots.

Diese Dissertation ist ein Blick in die Zukunft. Sie diskutiert die E-Bike City und den Wechsel hin zur "kleinen Infrastrukturäls alternatives Paradigma der Verkehrspolitik in Agglomerationen. Die Ergebnisse bilden eine Grundlage für zukünftige Arbeiten in der Forschung und in der Praxis. Sie zeigen auch, dass ambitionierte, aber umfangreich geplante Interventionen eine nachhaltige Transformation von städtischen Verkehrssystemen ermöglichen können. Die Dissertation beantwortet ihre übergreifende Frage, wie die E-Bike City in Zürich funktionieren würde und stellt Werkzeuge bereit, um das Konzept in Zürich, sowie an anderen Orten weiterzuentwickeln.

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Notes on the usage of generative AI

Parts of this dissertation were enhanced for grammar, more accurate wording, and better readability using generative AI. The process applied was as follows: A first draft was written manually. Then, a chat was created in ChatGPT (GPT-4o model), with the following initial prompts: ”I wrote the following paragraph in latex. Please improve the grammar and scientific writing style but keep the latex code formatting”, (Uploading the most relevant sources), ”Use the terminology from these documents in the responses”. Next, individual paragraphs from the draft were copied into the chat. The responses were either used directly or as inspiration for further improvements. Finally, further revisions were performed manually and Grammarly was used to identify and fix any grammar issues introduced in this process.

In some cases, ChatGPT was used to provide inspiration for structuring entire sections but without directly using the results. Here, the process included uploading the entire dissertation draft and asking high-level questions like ”write a possible summary”, ”list the most important conclusions”, or ”identify any contradictions”.

Finally, ChatGPT was used to create complex formatting structures in LaTeX, such as tables or special adjustments in the overall formatting.

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Chapter 1: Introduction

Well-functioning transportation is vital for modern societies. It enhances personal freedom, nurtures social equity, and stimulates economic growth. Reaching many destinations quickly and easily allows us to pursue the education we aspire to, spend time with friends we enjoy, and pursue occupations where we make the most out of our skills. Conversely, it allows firms to reach profitable customers, employers to draw on professionals with the most appropriate skills, and schools to attract the best candidates for their curriculums. We build roads, bridges, tunnels, and railway lines to increase these freedoms, encourage specialization, and generate a growing economic output.

However, traffic also comes at a massive cost to our public budgets, health, and environment. Building new infrastructure in dense and wealthy cities comes at an increasing cost and complexity, the transport sector is a leading source of carbon emissions, crashes are a major cause of death, and car-oriented lifestyles contribute to an epidemic of obesity.

Since ancient times, traffic congestion has been a plague of dense cities, later seen as a symptom of failed transport planning. However, focusing solely on solving congestion comes at the risk of missing important needs and potentials. Martens (2016) suggests that rather than removing bottlenecks, transport planning should focus on managing accessibility[1] provided to each population group. In such practice, transport systems can be developed precisely to provide improvements for people who need them the most, rather than those who happen to be affected by bottlenecks.

Rapid urbanization, aging urban infrastructure, overstrained public budgets, and the need for rapid decarbonization place great demands on city planners. Their work should stimulate economic growth, reduce public spending, and enable a transition to net-zero emissions. However, the policy discussions they engage in are massively hindered by dilemmas between these goals (Axhausen, 2022). Supporting economies through expanding transport infrastructure in dense areas comes at rapidly growing costs and complexity. Simultaneously, faster and cheaper transportation on new roads invites more travel, erasing even much of the reductions in pollution created by better, more efficient technology. Paradoxically, even more sustainable vehicles, such as electric cars, tend to induce more travel through lower operating costs. These fundamental relationships make it difficult to continue increasing accessibility at a reasonable cost and simultaneously decarbonize the transport sector. As a result, the development of future transport policies is hindered by unfruitful iterations between these goals.

Kuhn (1962) argues that scientific progress occurs in a sequence of paradigms. Once a paradigm fails to provide a sufficient basis for progress, it eventually becomes succeeded by a newer one. This dissertation applies the same lens to the chal-

1 Accessibility is a measure of the ease of reaching destinations such as jobs, schools, or friends. It can be improved by faster or easier transportation or a higher density of destinations; see Hansen (1959) for a common definition.

lenges of today's transport policy discussions. Decarbonizing urban transportation rapidly enough, maintaining economic growth, and housing millions of additional people in cities seem impossible by continuing along the current path. Only a quantum leap, created by shifting to a new paradigm in transport planning, may enable us to fulfill these goals.

Dating back to the urban visions of Le Corbusier or Frank Lloyd Wright, today's paradigm favors accessibility gains through high speeds and travel time savings. We built large pieces of infrastructure to allow fast travel over long distances. However, recent popular discussions about "15-Minute Cities" and urban "Superblocks" suggest the emergence of a new paradigm focused on safety, comfort, and flexible travel across short distances. Even in Switzerland, recent public votes confirm the wish for change: In September 2024, citizens in the City of Zurich voted for reallocating 1% of road space to safe cycling paths and greenery every year (i.e., 30% in three decades). Two months later, a referendum at the federal level declined a set of proposed highway system extensions[2].

This dissertation discusses an alternative to the present paradigm, emphasizing "small" rather than "large" infrastructure. It advances the idea of an *E-Bike City*, originally suggested by Axhausen (2022) and addresses the following overarching question: How will an E-Bike City work in the context of Zurich?

THE E-BIKE CITY PROJECT The work for this dissertation was done as part of a larger research initiative, the E-Bike City Project, at the Department of Civil and Environmental Engineering, between 2022 and 2025. It aims to break through the present dilemmas of transport policy by testing a large change. As a starting point, it assumes to dedicate 50% of road space to small, lightweight modes such as bicycles and e-bikes by restructuring the organization of traffic, mainly into a system of one-way streets. While this dissertation focuses on the overall design and its impacts on accessibility, other researchers explore complementary aspects and questions related to the hypothetical transformation[3]: Optimal design of public transport services under changing demand (Martin-Iradi *et al.*, 2024; Gallo *et al.*, 2023), design norms for streets and intersections, exploring the possibilities of dynamic road space allocation (Ni *et al.*, 2024; Fulton *et al.*, 2025), mathematical optimization and assessment of the network designs (Wiedemann *et al.*, 2025; Grisiute *et al.*, 2024), environmental impacts (Peiseler *et al.*, 2024; Schenker *et al.*, 2022, 2024), political acceptance (Wicki and Kaufmann, 2024; Elliot *et al.*, 2024), modeling the impacts (Meister *et al.*, 2024, 2023; Heinonen *et al.*, 2024; Meyer De Freitas and Axhausen, 2024), safety effects and cost estimates (Zani *et al.*, 2024; Elvarsson *et al.*, 2024), and modeling changes in activity patterns (Pougala *et al.*, 2022; Manser *et al.*, 2024; Pougala *et al.*, 2023). Together, these interdisciplinary efforts aim to provide a holistic understanding of how the E-Bike City model can function as a viable alternative to the conventional transport planning paradigm.

2 see "Gegenvorschlag Zukunfts-Initiative" and "Gute-Luft-Initiative" for Zurich, as well as the "Federal Decree on the 2023 expansion program" for the national highways

3 For a full list of related contributions, see `https://ebikecity.baug.ethz.ch/en/`

1.1 Overview of the Dissertation

This thesis makes four linked contributions: (1) Theorizing a functional concept of the E-Bike City, as well as the detailed research questions to be addressed, (2) Introducing a process for designing the transport network of an E-Bike City in a rapid and reproducible way (3) Providing typical street designs and visual previews of the E-Bike City in Zurich, as well as a design manual for other places, and (4) Assessing the impacts of such transformation on mode shares and accessibility in the greater Zurich area. See Figure 1.1 for an overview of the thesis structure.

1.1.1 The E-Bike City concept

The early ideas of an E-Bike City suggest reallocating approximately 50% of road space from motorized traffic to separated infrastructure for small, lightweight modes such as bicycles and e-bikes (Axhausen, 2022). The quality of public transport will remain at least at the current level, and every building will still be accessible by car through a system of one-way and limited-access streets.

Developing tangible designs of how such an idea will work in Zurich requires a functional concept. Therefore, Chapter 2 addresses how to design the E-Bike City as a tangible new starting point for transport policy discussions.

Building on a wide range of literature from transport planning, urban visions, and social equity, it theorizes the E-Bike City and translates it into specific design challenges. It expands the discussion on present barriers to decarbonization of transport, the dilemma between accessibility and sustainability, and ways of overcoming it by creating a new starting point for transport policy discussions. Based on this conceptual framework, it formulates a set of specific challenges that need to be addressed in the design and proposes a research agenda for creating and understanding the designs. Finally, great attention is dedicated to discussing the effects on social equity and ways of managing them.

The foundational work in this chapter structures the rest of this dissertation and motivates the research questions in the following chapters.

1.1.2 Rapid and reproducible design of alternative transport networks

Experimenting with different variants of the E-Bike City requires practical tools for rapid and reproducible modeling of alternative transport networks. The global availability of open geographic data and the large computing power of standard computers make it possible to generate realistic networks for entire cities automatically and almost in real time. Multiple algorithms have been proposed for an automated generation of cycling networks or an optimization of public transport services anywhere in the world. Being able to rapidly generate and test such alternative transport networks enables planners to explore a wide range of options beyond a mere optimization within current practice.

However, in practice, the possibilities of transport planning in dense urban environments are highly restricted by available road space and numerous constraints due to the coexistence of

Figure 1.1: Structure of the dissertation

different modes. This is especially true for the E-Bike City, as a policy that focuses on repurposing the existing facilities rather than building new ones. So far, none of the available algorithms can be used for such planning tasks at the scale of entire cities.

Thus, the research question addressed in Chapter 3 is how to model the E-Bike City (and possibly other alternative futures) as realistic, multi-modal transportation networks in a rapid and reproducible way. It provides a process for generating and testing alternative networks automatically based on road space data from open sources and a set of user inputs. It considers the constraints of existing road space, needs for car access, dependencies between lanes and public transport routes, and a flexible set of design rules and goals that can influence the results. For example, users opt to win space for cycling infrastructure by reducing car traffic to one-way streets. The resulting network design can be exported to common traffic simulation tools, such as MATSim. The process introduced in this chapter is implemented in a Python software package SNMan (Street Network Manipulator)[4]. It is available as open-source software and can be used by practitioners to test ideas for future transport plans in any city worldwide.

While the previously available tools and algorithms are suitable for small-scale proofs of concept or initial cycling network ideas without considering further details, the software SNMan introduced in this chapter can generate holistic designs for multi-modal transport networks driven by custom design rules.

4 `https://github.com/lukasballo/snman`

1.1.3 Designs for streets and intersections

Succeeding in the sustainable transformation of urban mobility requires a high level of information, empowerment, and consistent policy direction (Banister, 2005). A tangible representation of what life could be and feel like in an alternative urban future is essential for making informed decisions about adopting a new paradigm.

With the recent rise of generative models[5], planners can create visual designs of urban environments quickly and in an automated way. Images of popular places with grass instead of asphalt or cycling paths instead of travel lanes can be generated in seconds and inspire new lines of thought.

However, similarly to the cycling infrastructure algorithms mentioned in the previous section, such representations can easily miss important contexts and constraints that emerge from the systemic nature of transport networks. As a result, they often resemble utopias, far from what is practically feasible.

Therefore, Chapter 4 is motivated by the question of how the E-Bike City will function, look, and feel—while ensuring a functional transportation network. It introduces alternative designs of four locations in Zurich, each representing a different set of distinct challenges and trade-offs. The designs were developed in a workshop involving researchers, students, and experts. Appendix A provides a set of generalized standards that can be applied to other, similar cities.

The designs introduced in this chapter aim for attractive and functional environments at the microscopic level while at the

5 For example, `https://site.urbanistai.com/`

same time ensuring consistency across the network. Unlike many out-of-context designs proposed by generative models, they provide a tangible preview of an alternative, yet practically feasible, future.

1.1.4 Accessibility effects

As mentioned at the beginning of this introduction, the traditional transport planning paradigm emphasizes large, high-profile pieces of infrastructure that allow traffic at high maximum speeds. Consequently, measures that restrict car access trigger fears of accessibility losses. On the other hand, the E-Bike City produces accessibility through the ease and flexibility of cycling, enabled by modular, low-cost interventions. Considering the impacts on each mode independently, these two paradigms are *incommensurable* in Kuhn's terms (Kuhn, 1962): The former saves drivers' time while the latter improves the safety and comfort of cyclists. Only through a multimodal view do the effects become comparable.

In addition, the spatial distribution of accessibility effects is different in each paradigm. As a result, transitioning to the E-Bike City results in gains for some population groups and losses for others. Understanding these patterns is essential to judge the desirability and fairness of such a paradigm. However, so far, no assessments have been conducted that study the effects of such far-reaching interventions on the scale of entire cities and metropolitan regions.

Therefore, Chapter 5 addresses two research questions: (1) What are the overall impacts of the E-Bike City on accessibility and mode choice? and (2) How are the impacts distributed across different groups of people? It models the traffic impacts in MATSim and compares the resulting accessibility structures using the logsum accessibility (Ben-Akiva and Lerman, 1979), rooted in random utility theory. The simulations were performed on an alternative network generated in Chapter 3. The impacts on each person in a random population sample were grouped according to different individual characteristics (age, sex, driver's license ownership, urban vs. suburban).

1.2 Publications

Parts of this dissertation are based on publications listed in a separate chapter at the end. The Chapters 2 and 3 are slightly updated versions of peer-reviewed journal publications. Chapter 4 and Appendix A are the results of design workshops conducted throughout the E-Bike City project. Chapter 5 and Appendices C-D are based on a conference paper but were extensively updated and rewritten. A full list of publications produced during this thesis can be found on the last pages of this dissertation.

Chapter 2: The E-Bike City Idea

This chapter is based on the following peer-reviewed journal paper:

Ballo, L., L. Meyer de-Freitas, A. Meister and K. W. Axhausen (2023) The E-Bike City as a radical shift toward zero-emission transport: Sustainable? Equitable? Desirable?, *Journal of Transport Geography*, **111**, 103663.

It is reproduced with formatting adjustments and minor corrections. The individual contribution of Lukas Ballo is the conceptualization and writing of the manuscript. The other co-authors provided inputs and revisions.

2.1 Introduction

The transport sector must reduce its carbon footprint by at least 59% by 2050 (IPCC, 2022). It is also under pressure to reduce its other negative externalities, such as accidents, noise, and extensive usage of public space (Moreno *et al.*, 2021). At the same time, investments in better road infrastructure generate economic value through accessibility improvements but also lead to induced traffic (Hymel *et al.*, 2010; Hymel, 2019; Great Britain Department of Transport, 1994; Duranton and Turner, 2011). This trend is further amplified by population growth (UN, 2019) and increasing wealth (Steffen *et al.*, 2015).

The global population in cities is expected to grow by 58% from 2018 to 2050. Most of this growth will happen in less developed regions (UN, 2019), often with weak institutional practices of spatial and transport planning. The vast majority of surface-bound passenger travel is using private cars, most often occupied by solo drivers (BFS and ARE, 2023), resulting in high energy consumption, substantial negative externalities, and carbon emissions (ITF, 2020). Globally, the mode share of private cars is estimated at 71% of passenger kilometers (PKM) in urban areas (Aguiléra and Grébert, 2014). Even in Switzerland and the Netherlands, despite a relatively robust supply of alternatives, the mode share of private cars accounts for roughly 69% and 71% of PKM, respectively (BFS and ARE, 2023; KiM, 2022). Car driving is further perpetuated by building codes requiring a generous provision of (uncharged) parking, making all tenants and homeowners involuntarily pay for the car-centric transport system (Shoup, 2005). At the same time, this reduces the supply of commercial and residential space, particularly in North America, where parking typically consumes around 5% of total urban land to provide 2.5 to 3 parking spaces per vehicle (Davis *et al.*, 2010).

Since the COVID-19 pandemic, the "new normal" has further exacerbated already existing challenges. A study in Switzerland has shown that road traffic volumes have quickly returned to their pre-pandemic levels (Molloy *et al.*, 2021). At the same time, falling transit ridership, partially paralleled by growing car ownership, poses fiscal challenges to transit agencies (Basu and Ferreira, 2021). Recent studies suggest an increased preference for solo driving over more sustainable collective modes (Abdullah *et al.*, 2021; Basu and Ferreira, 2021;

Das *et al.*, 2021). Less regular commuting may further reduce revenues from season tickets (Axhausen, 2020). Policymakers need to find new ways of securing transit financing and managing road traffic volumes.

Although much hope has been placed on the technical progress of battery-electric vehicles (BEV) to mitigate climate change, realistic scenarios show that this will not decarbonize transport quickly and strongly enough (de Blas *et al.*, 2020; Gebler *et al.*, 2020). BEVs still produce substantial greenhouse gas (GHG) emissions throughout their lifecycle and do not address many other negative externalities of traffic, including accidents or the excessive use of space. As of 2020, the lifecycle CO_2 emissions of private BEVs were only roughly 25% lower compared to vehicles with internal combustion engines (ICE) (ITF, 2020). Depending on the exact vehicle model and the location where the vehicle is charged, many BEVs in the US currently produce more emissions than equivalent hybrid-electric vehicles (Singh *et al.*, 2023). Cox *et al.* (2018) estimate that future BEVs may generate lifecycle GHG emissions of 45 to 78% of today's values, although parts of the necessary technologies are still in the prototype stage (IEA, 2021).

Moreover, ongoing technical progress in electric vehicles will likely decrease the generalized cost of driving below the current levels, thus inviting additional demand (Wang *et al.*, 2021). While the lifecycle costs of BEV and ICE vehicles are approximately equal today (Verma *et al.*, 2022), falling battery costs will make BEVs cheaper (Schmidt *et al.*, 2017). The emergence of autonomous vehicles will further accelerate this trend by lowering the generalized cost of car travel (Bösch *et al.*, 2018; Steck *et al.*, 2018), enabling a wider group of potential users and perpetuating urban sprawl (Meyer *et al.*, 2017). As a result, a large part of the BEV sustainability benefits will be counterbalanced by induced demand, in line with Jevon's Paradox – see Alcott (2005) and Sorrell (2009). The car has been a critical driver of economic growth since the early 1900s, with many jobs dependent on its supply chains. Attempting to retain this model while at the same time addressing the climate crisis, transport policy is caught in a dilemma between maximizing accessibility and making transport sustainable (Axhausen, 2020, 2022). This chapter aims to catalyze a discussion about ways out of this dilemma. The remainder of this chapter is structured as follows: Section 2.2 presents an overview of behavior changes necessary for effective transition paths to sustainable mobility. Among different ways to achieve such changes, it emphasizes the potential of urban visions that positively frame future travel behaviors. Section 2.3 proposes the E-Bike City as a new starting point for urban transport policy discussions. Section 2.4 elaborates on changes in accessibility patterns that may emerge from such policy direction in existing cities. Section 2.5 outlines potential barriers and emerging avenues of research, followed by a conclusion in Section 2.6.

2.2 Behavior change for sustainability

2.2.1 Necessary and possible

As shown in the introduction, technical progress alone is insufficient for decarbonizing transport within the necessary time frame. A substantial body of literature concludes an inevitable need for large behavior changes alongside technical progress (de Blas *et al.*, 2020; Grubler *et al.*, 2018; Moriarty and Honnery, 2013). Multiple studies have analyzed the potential of such behavior changes (see Creutzig (2019); Santos (2017); Banister (2011); Santos *et al.* (2010); Zhang and Zhang (2021). Experience from the COVID-19 pandemic shows that substantial changes in travel behavior are possible (Molloy *et al.*, 2021). However, the following sections illustrate how difficult it is to induce them under normal conditions.

2.2.2 Supply-side changes

MOBILITY PRICING A frequently discussed way of changing travel behavior is through comprehensive pricing (Levinson, 2010). Such schemes may focus on internalizing the adverse external effects of carbon emissions, noise, usage of space, accidents, etc., and helping to maintain desirable levels of service in traffic. Successful examples from Stockholm, Milan, London, New York City, and Singapore (Croci, 2016; Schaller, 2010; Anas and Lindsey, 2011) show that such measures are, in principle, possible and effective. However, evidence from democratic countries also shows that implementing such measures is highly unpopular and politically unfeasible on a larger scale (Jakobsson *et al.*, 2000; Gu *et al.*, 2018; Lichtin *et al.*, 2022). Even payment for parking is contested in many places (Shoup, 2005).

LAND USE AND TRANSIT In the long term, mode choices or, more generally, the amount of travel may be influenced by changing land-use patterns or providing attractive transit options. Public transport's lifecycle GHG emissions per PKM are roughly 50-70% lower compared to private cars (ITF, 2020). Its use of road space is about 16 times more efficient in terms of passengers/hour on a single traffic lane (NACTO, 2016). However, the time needed to implement land-use changes and transit is too long, given the urgency of the climate crisis. Also, the benefits of residential areas favoring car-free lifestyles, such as transit-oriented development (Ohland and Dittmar, 2004; Calthorpe, 1993), can vanish over time if high property values attract groups with high car ownership rates (Paul and Taylor, 2021; Steuteville, 2017).

CYCLING INFRASTRUCTURE A different type of behavior change could be induced by encouraging shifts to active modes with light and energy-efficient vehicles. Over the entire lifecycle, cyclists on privately owned e-bikes emit 5 times less GHG per PKM than car users (10 times less in the case of conventional bicycles) (ITF, 2020), and a single traffic lane can carry 5 to 12 times more passengers per hour on bicycles than in private cars (NACTO, 2016). Besides low emissions and high space efficiency, widespread cycling may also increase transit catchment areas, making demand bundling on existing infrastructure easier. Finally, compared to car traffic, cycling produces substantial health benefits (Garrard *et al.*, 2021), resulting in net positive externalities (ARE, 2022). Many individuals would, in principle, be willing to cycle if it were safer (Dill and McNeil, 2016; Geller, 2009). Providing a safe cycling infrastructure is therefore an essential instrument for inducing the shift (Pucher and Buehler, 2008). Since the 1990s, New York, San Francisco, Portland, London, Paris, Berlin, Seville, Bogotá, and many other cities have increased their modal splits of cycling by investing in safer, dedicated infrastructure for cyclists (Pucher *et al.*, 2021). Unprecedented progress happened during the COVID-19 pandemic, with massive networks of pop-up bike lanes deployed in many prominent cities, e.g., Paris, London, Washington DC, and Boston (Buehler *et al.*, 2021; Kraus and Koch, 2021; Becker *et al.*, 2022), many of which have remained until today. Active modes are increasingly seen as a functional solution to multiple challenges of transport policy (Fishman, 2016; Parkin, 2012; Pucher and Buehler, 2017), and the recent developments may be a starting point for discussions about more radical changes in urban transport systems in the post-COVID-19 world. However, despite the growing popularity of cycling policies, it is still unclear to what extent cycling could replace a substantial part of private car trips and what the consequences would be.

2.2.3 Demand-side changes

POOLING The average car occupancy in Switzerland is 1.53 passengers, resulting in a load factor of 31% (BFS and ARE, 2023). With 69% of car capacity unused, increasing the occupancy could substantially reduce the volume of traffic. Pooling in relatively small paratransit vehicles is popular in emerging countries (Behrens *et al.*, 2016), as there are few alternative modes of transport. However, it remains a marginal phenomenon wherever solo driving is affordable. Evidence from the US shows that pooling is largely limited to low-income communities lacking alternatives (Shaheen, 2018) and mainly draws passengers from public transit (Shaheen *et al.*, 2016). For similar reasons, even the large-scale potential of autonomous pooled taxis is contested (Alonso-González *et al.*, 2021; Becker, 2020).

WORKING FROM HOME Working from home can reduce the need for commuting (Delventhal *et al.*, 2022). However, rebound effects would likely shrink the resulting benefits (O'Brien and Yazdani Aliabadi, 2020). A GPS tracking study in Switzerland during and after the initial stages of the pandemic shows that road traffic returned to its original levels within five months despite an unprecedented increase in work from home (Molloy *et al.*, 2021). Older studies on "telecommuting" also suggest that working from home bears no substantial potential for reducing car travel, given long-term rebound effects (Choo *et al.*, 2005; Zhu and Mason, 2014).

2.2.4 Urban visions as enablers for transport policy discussions?

Unlike traditional measures for controlling travel demand via pricing and restrictions, positive images such as 15-Minute Cities (Moreno *et al.*, 2021) or Superblocks (Rueda, 2019) enjoy a rather favorable discussion despite aiming for similar goals. Through their positive reception, they open ways of rethinking elements of urban planning that might otherwise not be negotiable. In such cities, sustainable mobility can enjoy a universal preference without the possibility of some groups buying themselves out. The practical complexities may only become apparent later, once the public is enthusiastic about the benefits of living in such cities.

Images of modern urbanism from the beginning of the 20th century also enjoyed great popularity and shaped urban planning throughout the rest of the century. Visions like Le Corbusier's *Ville Radieuse* (Le Corbusier, 1935), Frank Lloyd Wright's *Broadacre City* (Wright, 1932), or Hans Bernhard Reichow's car-oriented city *Autogerechte Stadt* (Reichow, 1959) quickly won the favor of the public, while the resulting traffic and parking challenges only became apparent later.

Observing the normative power of such urban visions, the question arises as to whether the enthusiasm they produce could be used to open a stream of more ambitious transport policy discussions. As a starting point for this discourse, we propose to explore the feasibility of an E-Bike City, building on early ideas in (Axhausen, 2022).

2.3 The E-Bike City

2.3.1 The basic idea

The E-Bike City aims to provide a new starting point for transport policy discussions. It should mobilize research to test the feasibility of an urban transport system based primarily on active mobility and public transit, potentially opening new pathways for future transport policies. Its core idea is allocating road space in favor of transit, walking, and cycling while incorporating e-bikes as an accelerator for longer trips and wider user groups. As an initial assumption, it may dedicate approximately 50% of the existing road space to cycling while leaving the remaining space for motorized traffic, mainly in the form of one-way streets. A generous provision of dedicated infrastructure would make cycling attractive to a wide spectrum of users. Public transit would allow longer trips and complement cycling when it is not feasible. On the other hand, reducing road space for motorized traffic would make driving less attractive, further encouraging a shift to sustainable modes.

The recent mass availability of e-bikes and other micro-mobility vehicles, such as cargo bikes or e-scooters, massively broadens the potential appeal compared to traditional bicycles. They allow longer trips and reduce the impact of elevation differences (Rérat, 2021; Meister *et al.*, 2023; Meyer de Freitas and Axhausen, 2023; Bourne *et al.*, 2020; MacArthur *et al.*, 2018). Using e-bikes helps increase cycling frequencies (Van Cauwenberg *et al.*, 2022; Edge *et al.*, 2018) and maintain cycling despite changing circumstances (Marincek and Rérat, 2021) and is being seen as an enabler, strengthening transition pathways (Edge *et al.*, 2020). Giving wider user groups the capability to cover short and medium distances using micro-mobility improves the cost-effectiveness of transit systems by allowing stronger demand bundling on lower-density networks with longer stop distances.

In contrast to more extreme visions of cycling cities like Velotopia (Fleming, 2017) or Bicycle Utopias (Popan, 2019), the E-Bike City should not be seen as a unimodal utopia but rather as a means of seeking a new balance between existing modes of transport. Its streets would still permit private car travel, although possibly at lower speeds and with some detours. The available road capacity could be priced or otherwise managed to ensure a sufficient level of service for essential trips and commercial and emergency vehicles.

A conscious supply of public and private parking spaces would help manage both the demand for driving and car ownership rates. It would also help provide more space for commercial, residential, and public uses – resulting in more local businesses, affordable housing, and attractive street spaces. Fully internalizing the cost of parking to its users would relieve car-free households from the cost of car traffic and incentivize economically efficient mode choices.

Similar to the pop-up bike lanes implemented in response to the COVID-19 pandemic, the E-Bike City could be started by merely repainting existing road surfaces, at first, perhaps, as a set of temporary pilots. Experimenting at little cost and with immediate results would replace lengthy planning processes. If successful, the first progress toward healthy and sustainable cities would be achievable within a few years.

The E-Bike City vision is a research agenda for a way out of the present transport policy dilemma by exploring to what extent future transport planning could utilize the potential of active mobility. The following section outlines its key challenges, together with areas of research to address them.

2.3.2 Addressing practical challenges

LONG TRIP DISTANCES Decades of car-centric lifestyles have created urban geographies that are difficult to serve by modes other than private cars (Illich, 1974). Long distances and dispersed travel patterns in sprawling cities and agglomerations are a considerable challenge for sustainable mobility transitions. However, the vast majority of trips in Western metropolitan areas are still short, well within the range of e-bikes, possibly in combination with public transit. Assuming an average e-bike speed of 22 km/h for longer trips (Lopez *et al.*, 2017), distances of up to 11 km are attainable within a travel time of 30 minutes. Faster micro-mobility vehicles such as s-pedelecs with average speeds of 22-25 km/h (Schleinitz *et al.*, 2017) could extend the viable distances even further. In the greater Zurich area (Kanton Zürich), including suburban and some rural areas, 65% of passenger car trips are within 10 km, and 75% are within 16 km (Hofer, 2017). In the major US metropolitan areas of San Francisco, Boston, Chicago, and Atlanta, 72-77% of passenger car trips are within 16 km (Federal Highway Administration, 2020). Despite concerns over range anxiety (Edge *et al.*, 2018), entire chains of such trips are well within the range of standard e-bike batteries, typically lasting for 50-80 km (Robert Bosch GmbH, 2023b). Intercommunal cycling "super-highways" (Rich *et al.*, 2021; Hallberg *et al.*, 2021; Pucher and Buehler, 2017) could help maximize the distances that can be covered using micro-mobility. Longer trips could leverage public transit, mainly using existing networks even if they have low density. However, the real potential, given daily activity chains, personal capabilities, and cargo loads, remains unclear. Future research is needed to show a more accurate estimate of trips that are feasible with active modes under real conditions and constraints.

WEATHER In large parts of North America and Northern Europe, cold temperatures and icy streets challenge the safety and comfort of users. Rainfall and heat also reduce the attractiveness of cycling. In an E-Bike City, users would have an alternative offered by public transit services, although the travel times might be longer and the overall cost higher for such occasional trips. Nevertheless, evidence from Germany suggests that high cycling levels are associated with lower sensitivity to weather conditions. In cities with high levels of cycling, the weather-based variation in bicycle counts during morning peak hours is under 5% (Goldmann and Wessel, 2021). To reduce the weather sensitivity further, E-Bike Cities could incorporate existing biodiversity efforts connecting green spaces (Kong *et al.*, 2010; Parker *et al.*, 2008) to create a primary network of cycling streets where greenery protects against rain and heat. Finally, a lasting increase in working from home could imply more flexibility in deciding when to travel, shifting travel demand to times with better weather conditions. To gain a fuller understanding of these effects, future research should explore the demand variations closer and show how they impact the usage of alternatives like public transit. If many cyclists turn to transit on rainy and cold days, research should show possible ways of operating rail and buses under such conditions.

USER CAPABILITIES Bicycle usage is limited by personal capabilities, e.g., leading to substantially lower speeds for the elderly (Schleinitz *et al.*, 2017). However, electrification helps even less able-bodied groups to stay mobile (Leger *et al.*, 2019; Meyer de Freitas and Axhausen, 2023). The wide range of available micro-mobility vehicles and safe infrastructure could help people with disabilities to move independently. On the other hand, electric micro-mobility vehicles of different sizes, weights, and speeds present a challenge for infrastructure design, requiring new approaches and quality measures (Kazemzadeh and Ronchi, 2022). While higher speeds may lead to more dangerous behavior (Vlakveld *et al.*, 2021), users of electric vehicles still seem to violate traffic rules no more often than those with non-electric vehicles (Langford *et al.*, 2015), and the overall safety of e-bike users appears to be similar to those using conventional bicycles (Jenkins *et al.*, 2022). Given the wide variety of electric and human-powered vehicles needed to make active mobility a primary mode of transport, future research should show what infrastructure will be needed, how it can be integrated into existing streets, and how it performs compared to traditional car-based transport systems.

PARKING Large quantities of (electric) micro-mobility vehicles of different sizes would require parking facilities, and the high value of e-bikes and cargo bikes creates a need for weather and theft protection. In cases where micro-mobility replaces car trips, parking can be provided by reallocating existing car parking spaces. However, if cycling replaces short transit trips, additional space for bicycle parking may be needed, particularly at central locations. Studies of travel behavior in E-Bike Cities should clarify the number and type of bicycle parking spots needed.

CHARGING The batteries of private e-bikes will put some additional load on the power grid, but even a massive usage is unlikely to create relevant challenges. Typical e-bike chargers, with a power rating of 0.1-0.3 kW (Robert Bosch GmbH, 2023a), correspond to roughly one to five incandescent light bulbs, which were in wide use until the early 2000s. This is in sharp contrast to standard home chargers for BEV, which have a power rating of up to 11.5 kW (Tesla, 2021) and 250 kW in the case of "superchargers" (Tesla, 2023). A typical e-bike battery has a capacity of 0.5-0.75 kWh (Robert Bosch GmbH, 2023b) – less than 1% of a Tesla Model S battery with up to 100 kWh (EV Database, 2023). The power consumption of a typical e-bike is approximately 0.01 kWh/km, over 90% less compared to the Tesla Model S (EV Database, 2023). Nevertheless, issues of power consumption, potentials of power storage, as well as lifecycle emissions remain a concern. Future research should deepen our understanding of these aspects in an E-Bike City, especially compared to other urban mobility futures.

VEHICLE AVAILABILITY In an E-Bike City, small micro-mobility vehicles are a crucial enabler for an achievable transition to sustainable urban mobility. But despite their growing popularity, their mass adoption faces an uptake barrier of purchase prices that are not affordable for some population groups (Jones *et al.*, 2016; Jenkins *et al.*, 2022). The E-Bike City may need to leverage large-scale sharing schemes to give everyone access to the vehicle they need. Even though shared vehicles are associated with higher lifecycle GHG emissions (Reck *et al.*, 2022), they may be crucial for low-income groups or could enable flexible trip chaining with public transit.

2.4 Accessibility effects

2.4.1 Changes in accessibility geographies

Accessibility refers to the possibility of reaching destinations from a particular place (Hansen, 1959) and is a crucial metric for transport and land use. Literature on equity suggests that transport systems should be designed to follow desired accessibility structures rather than aim for free-flowing traffic (Wee, 2011; Martens, 2016). However, accessibility is a complex measure. Depending on the question analyzed, components like travel time, comfort, or time-dependent opening hours of the different activities may be considered. In reality, each person's accessibility is also influenced by individual preferences and capabilities like vehicle and license ownership, bodily fitness, or time constraints. Therefore, accessibility has no single definition but needs to be tailored to each analysis. Here, we focus on the accessibility components of travel time and cyclists' comfort.

The reallocation of road space in the E-Bike City would substantially change the accessibility for cyclists and drivers. While drivers would experience longer travel times and detours due to reduced road capacity, reduced speeds, and one-way streets, cyclists would enjoy increased comfort while using the dedicated infrastructure. The resulting accessibility difference would result in mode shifts.

However, capabilities and preferences for changing modes vary across user groups. Depending on their degree of physical fitness or level of education, some users might be less inclined to switch to cycling, even with competitive travel times and better safety (Hudde, 2022; Meyer de Freitas and Axhausen, 2023). Also, the actual accessibility gains in cycling and public transit might not compensate for the travel time losses incurred by those currently driving. In particular, longer trips from outside of the city might be less attractive using transit and micromobility. On the other hand, some groups benefit from massively improved accessibility and independence once cycling becomes safer.

Table 2.1 shows estimated conceptual relationships of accessibility impacts on different user groups. We distinguish two types of urban settings representing simplified examples from industrialized nations: Cities with high density and strong public transit, and cities with low density and less attractive public transit. Within each city type, we consider city residents and suburban commuters, both with and without a car, all resulting in a 2x4 matrix of cases. The conceptual relationships are strongly simplified, representing the average situation of the exemplary groups, without considering cases under exceptional circumstances, such as cities where driving is already restricted to a minimum while allowing safe cycling. The following paragraph uses terminology from the scale below the table to describe the different levels of accessibility.

In dense cities with attractive public transit, urban residents without cars (H1) currently have "good" accessibility, greater than car-free residents in the suburbs, but less than their urban counterparts with cars. In an E-Bike City, their accessibility would increase through safer and faster cycling alternatives for shorter trips. On the other hand, those owning a car and enjoying the highest accessibility levels would experience longer travel times. Although the attractiveness of cycling would increase for this group as well, switching to cycling and transit would still likely result in slightly less accessibility for this group. Suburban commuters without a car (H3) currently have "poor" accessibility, less than all other groups. The E-Bike City's transit, optimized for fast travel across longer distances and safer last-mile cycling within the city, would increase their accessibility. Those with a car presently have substantially higher accessibility (H4) and would incur losses similar to group H2, reaching accessibility equivalent to their neighbors without a car.

In cities with low density and less attractive public transit, those without a car (L1) currently experience substantially lower levels of accessibility than their counterparts in high-density cities. In an E-Bike City, they would enjoy substantial gains due to attractive cycling and faster transit. On the other hand, those with a car (L2) would experience a loss, resulting in accessibility levels similar to those without a car. Suburban commuters without a car (L3), who currently experience the lowest accessibility among all groups, would experience gains similar to their counterparts in high-density cities, but their accessibility would remain "bad". Those with a car (L4), on the other hand, would incur longer travel times, but driving would likely still provide them better accessibility in comparison to the previous group.

Overall, the groups already using sustainable modes of transport would gain accessibility, while those driving would lose some. Large gains would be experienced by residents living in low-density cities without a car, possibly correlating with low-income communities. However, the exact losses for car owners might vary strongly depending on how the future

Table 2.1: Eight combinations of urban typology and population groups, together with a conceptual estimate of what accessibility changes they would experience (accessibility before → after)

	City residents		Suburban commuters	
	(1) without car	(2) with car	(3) without car	(4) with car
(H) High-density city with attractive public transit	**H1** + → + + (gain)	**H2** + + + → + + (loss)	**H3** - → o (gain)	**H4** + → o (loss)
(L) Low-density city with unattractive public transit	**L1** - → + (large gain)	**L2** + + → + (loss)	**L3** - - - → - - (gain)	**L4** o → - (loss)

Accessibility scale:

+ + + Highest
+ + Excellent
+ Good
o Fair
- Poor
- - Bad
- - - Lowest

conception of transit systems provides alternative travel options over longer distances. Also, those switching from driving to cycling might experience additional losses due to discomfort. Further research is needed to better understand the expected changes in accessibility structures and how they correlate with existing lines of division in society.

2.4.2 Distributive justice and equity

The previous section outlined the conceptually expected accessibility changes and introduced a set of questions to be explored in future research. This section focuses on possible implications for distributive justice and social equity.

The Production of Space (Lefebvre, 1991) calls for a definition of space through social relations rather than its physical characteristics. Along these lines, a city is a place of social exchange to which every person should be entitled; see also The Right to the City (Lefebvre, 1972). Theories of transport justice frame this right through the concept of accessibility, combined with theories from political philosophy. According to Spheres of Justice (Walzer, 1983), some goods should be excluded from a free exchange due to their special meaning in society. Applying Lefebvre's point, social interaction is one such good. The Capability Approach (Sen, 2009) identifies the mere possibility of accessing destinations as essential, regardless of whether they are reached. The Difference Principle (Rawls, 1999) marks the importance of redistributing resources to those who are worst off (such as those with low accessibility). And finally, the theory of "auctions and insurance schemes" in (Dworkin, 2000) justifies partial compensations for those incurring unjust accessibility deficits.

Building on these theories, Pereira *et al.* (2017) propose that distributive justice concerns over transport and social exclusion should primarily address accessibility as a human capability. Following this argument, the social equity of transport policies is mainly a question of groups experiencing the lowest accessibility to key locations. Transport Justice (Martens, 2016) introduces an analytical method of evaluating the social equity of real transport-land use systems. In Martens's view, transport planning must aim to provide every population group with at least a basic level of accessibility above a sufficiency threshold. In contrast to these accessibility-centric theories, Gössling *et al.* (2016) adopts a wider view of transport injustices in three dimensions: exposure to traffic risks and pollutants, distribution of space, and the valuation of travel time. He concludes that pedestrians and cyclists are the most sustainable participants in urban contexts, yet are particularly often affected by the negative effects of motorized traffic, which is a clear case of injustice.

Taking the perspective of Gössling *et al.* (2016), the E-Bike City would mitigate the injustices in today's Western cities: It would reduce the pollution faced by cyclists and pedestrians and improve their safety. From the perspective of transport justice, it would reduce the accessibility disadvantage typically experienced by people who don't have access to cars. A notable instance of the E-Bike City improving the lowest accessibility levels would be the effects on car-free residents in low-density cities and suburban areas.

However, while reducing the injustice faced by some groups, the E-Bike City might also exacerbate the disadvantage of other people. Especially where living costs in dense urban areas are not affordable and property ownership is increasingly determined by inheritance (Adkins and Konings, 2020), underprivileged groups could face inequitable car dependency due to their involuntary choice of residential location. Reducing road capacity in favor of cyclists might deepen their inequitable disadvantages unless balanced in other ways.

The anticipated changes in accessibility structures could also challenge the relationship between urban and rural communities. While the former would benefit from fewer negative externalities from motorized traffic, the latter would face higher generalized costs on their trips into the city. Although such changes would correct existing injustices in terms of Gössling *et al.* (2016), their distributive effects might create substantial controversies over different groups' "right to the city".

In summary, the E-Bike City could help weaken existing injustices between different population groups and their modes of transport. It could also benefit those groups experiencing the lowest accessibility because of no car ownership. However, its pure form in existing car-centric cities might increase injustices based on involuntary residential location choice and increase tensions between urban and rural communities unless addressed. To explore the feasibility and effects of an E-Bike City, further research is needed to understand its impacts on transport justice, given the existing spatial structure, social networks, and market conditions in real cities.

2.5 Getting there: Equitable and desirable?

Transitioning to a more sustainable transportation system is crucial for mitigating climate change. However, getting there in existing car-centric cities poses considerable challenges. In addition to improving sustainability, the proposed transition must avoid creating new injustices and be capable of gaining political acceptance. This section discusses a series of further issues that may be crucial to acquiring democratic acceptance of E-Bike Cities and implementing them.

The E-Bike City would favor those already using sustainable modes while producing losses for those presently driving. Designing proposals for real cities must involve tools for a precise understanding of the expected changes in accessibility patterns, how they relate to different population groups, and perhaps even to voting districts. Fine-tuning the exact road space allocation, changing public transit services, or adjusting the boundaries of areas where the transformation should be applied might play a key role in developing a proposal that is desirable for the majority.

The radical character of the proposal might also trigger fears of change. It might spur anxieties about the need for (unwanted) reorganization of everyday behaviors and changes in real-estate values (Liu and Shi, 2017; McDougall and Doucet, 2022). To address these concerns, the E-Bike City must emphasize its core vision and provide a locally embedded taste of it. Also, it must be transparent about the expected effects. Akin to Wright and Le Corbusier, the concept must be presented "not in dry formulas, but through three-dimensional models" (Fishman, 1982), creating strong positive images that will shape the planning process and the public discussion. As put by Banister (2005), sustainability policies must build on high levels of information, empowerment, and consistent policy direction to reach the required acceptance and impact.

2.6 Conclusion

Making urban mobility sustainable will demand a deep rethinking of transport policies, far beyond relying solely on technical progress. Behavior changes toward sustainable mode choices are an inevitable part of realistic pathways for addressing the climate crisis. The E-Bike City proposed in this think piece is intended to provoke a discussion about new directions for policymaking and inspire supporting research. It is meant to provide a taste of a sustainable mobility future, serving as a conceptual anchor for future work. Like Le Corbusier's and Wright's visions from the early 20th century, or the more recent 15-Minute Cities and Superblocks, the E-Bike City is designed to motivate scholars, policymakers, and the public to work toward a sustainable, equitable, and desirable urban future.

Chapter 3: Network Design

This chapter is based on the following peer-reviewed journal paper:

Ballo, L., M. Raubal and K. W. Axhausen (2024) Designing an E-Bike City: An automated process for network-wide multimodal road space reallocation, *Journal of Cycling and Micromobility Research*, **2**, 100048.

The content is reproduced with formatting adjustments and minor additions regarding the performance of the heuristic in comparison to mathematical optimization. The individual contribution of Lukas Ballo is the conceptualization, developing the underlying software, producing the results, and writing the manuscript. Martin Raubal and Kay W. Axhausen provided comments and revisions.

3.1 Introduction

In Chapter 2, we elaborated the "E-Bike City" concept, envisioning an urban transport system based mainly on public transport and small vehicles such as bicycles and e-bikes. Developing it further requires tangible designs and impact assessments. To create such designs in a reproducible way, we need a robust algorithm for generating city-wide cycling-oriented network designs while respecting the limited road space, as well as the dependencies within networks of lanes for motorized traffic and public transport.

However, the vast majority of existing methods for designing cycling networks in cities (Paulsen and Rich, 2023; Mahfouz *et al.*, 2023; Szell *et al.*, 2022; Steinacker *et al.*, 2022; Liu *et al.*, 2022; Castiglione *et al.*, 2022; Akhand *et al.*, 2021; Zhu and Zhu, 2020; Natera Orozco *et al.*, 2020; Caggiani *et al.*, 2019; Guerreiro *et al.*, 2018; Mauttone *et al.*, 2017; Duthie and Unnikrishnan, 2014) does not account for the trade-offs in road space allocation. To our knowledge, only two approaches consider the limited road space but either lack scalability beyond small network examples (Mesbah *et al.*, 2012), or are not yet able to consider the real-world interdependencies within multimodal transport systems (Wiedemann *et al.*, 2025), such as public transport routes, access to buildings, and parking needs.

In this chapter, we address this gap by introducing an automated process for generating network-wide road space reallocation schemes in real cities while considering the limited road space, as well as dependencies within the transport networks. The resulting designs can be visualized, evaluated with a set of metrics, or used as an input for traffic simulation toolkits. We use a case study in Zurich, Switzerland for demonstration. The process is implemented in a Python software package and made available open source, together with all data needed for reproducing the case study (see the end of this chapter for details).

Section 3.2 summarizes the previous work, Section 3.3 explains the conceptual design approach guiding the process, Section 3.4 shows the underlying methods, and Section 3.5

shows results from the case study in Zurich. Section 3.6 discusses the findings and the limitations, and Section 3.7 concludes the chapter.

3.2 Previous work

3.2.1 Cycling network design

Studies that introduce cycling network design algorithms can be divided into five groups. The first entails the generation of networks in real-world scenarios using greedy algorithms. Szell *et al.* (2022) 'grow' cycling networks by connecting a set of arbitrary points of interest using greedy triangulation, defining the order of implementation, and routing the connections onto the existing street network. Steinacker *et al.* (2022) generate bike lane networks that optimally facilitate trips in a bike-sharing system. They use an inverse network formation where, initially, all edges have bike lanes and are subsequently removed while prioritizing those whose removal has the smallest adverse effects on the cycling trips. Natera Orozco *et al.* (2020) generate additions to existing cycling networks to improve their connectivity by adding short missing pieces.

The second group focuses on prioritization within a set of possible cycling infrastructure projects. Paulsen and Rich (2023) use a novel technique of mapping the potential benefits predicted for individual origin-destination pairs onto the network and identifying the contributions of individual additions. Then, they prioritize them to maximize the net present value while considering the future benefits and construction costs. Mahfouz *et al.* (2023) present another integrated approach for prioritizing cycling facilities that involves cycling demand prediction, route calculation, and network analysis.

The third group (Liu *et al.*, 2022; Zhu and Zhu, 2020; Caggiani *et al.*, 2019; Guerreiro *et al.*, 2018; Mauttone *et al.*, 2017; Duthie and Unnikrishnan, 2014) uses optimization techniques to find networks of cycling facilities that maximize the benefits for cyclists (e.g., maximizing cycling infrastructure length) while minimizing the construction cost. The fourth group deals with less conventional approaches: DBSCAN clustering of GPS points from micromobility vehicles to identify potential corridors (Castiglione *et al.*, 2022) and using Physarium-inspired growth mechanisms (Akhand *et al.*, 2021).

Lastly, the fifth group addresses the trade-offs within limited road space. Wiedemann *et al.* (2025) allocate parts of the road space either to cycling lanes or general travel lanes and generate a Pareto frontier of travel times for cyclists (adjusted by comfort factors) and travel times for drivers (affected by detours after removing travel lanes). Mesbah *et al.* (2012) utilize a bi-level optimization, consisting of a genetic algorithm and a traffic assignment that produces an estimate of the resulting travel times for both cyclists and drivers. Along similar lines, Burke and Scott (2016) propose a framework to incorporate the disruption of motorized traffic by removing travel lanes. They use a Network Robustness Index (Scott *et al.*, 2006) to measure how critical a link is to overall traffic flow. It is calculated by performing a traffic assignment and calculating the resulting travel time changes for all trips. However, the traffic assignment in both Mesbah *et al.* (2012) and Burke and Scott (2016) involves a relatively high computational cost, thus substantially limiting the feasible network size and the number of design iterations.

The work presented in Wiedemann *et al.* (2025) introduces a mathematical optimization approach for allocating road space in a utility-maximizing way. Its performance is compared with three heuristics based on betweenness centrality, originally derived from Steinacker *et al.* (2022): starting from a full cycling network and subsequently adding car lanes (betweenness-top-down), starting from the present network and subsequently adding cycling lanes based on highest betweenness centrality for cyclists (betweenness-bottom-up (bike)), and same as the last one but with adding cycling lanes based on lowest betweenness centrality for drivers (betweenness-bottom-up (car)). The mathematical optimization massively outperforms the first two approaches in almost all cases along the Pareto frontiers. However, surprisingly, it is only slightly better than the betweenness-bottom-up (car) heuristic, in some cases offering roughly 5-10 percentage points higher reduction of perceived cycling travel time with the same changes to car travel time.

3.2.2 Network capacity

Network capacity can be expressed using Macroscopic Fundamental Diagrams (MFD). Loder *et al.* (2019) have analyzed the amount of motorized traffic that can be handled by urban networks. They have estimated a regression model that explains the form of the MFD, which shows the maximum trip production in vehicle-km per hour. It uses four network measures as inputs: road network density, betweenness centrality, intersection density, and bus production density. The maximum trip production of motorized traffic is increased by higher road network density, lower average betweenness centrality, lower intersection density, and lower bus production density. While this model does not consider cycling, it allows a quick approximation of how different network variations affect the motorized traffic, without the complexity of carrying out a traffic assignment.

3.2.3 Economic analysis

Transport investments and policy decisions are commonly assessed using a cost-benefit analysis (CBA). Comprehensive CBA studies related to cycling infrastructure (Rich *et al.*, 2021; Li and Faghri, 2014; Sælensminde, 2004) typically consider the construction and maintenance cost, personal travel cost savings, travel time savings, health care cost reduction, crash cost, and the benefits of reduced emissions. Sælensminde (2004) additionally considers the cost reductions for transporting school children, as well as the reduction of parking costs. Other CBA studies (Chapman *et al.*, 2018; Wang *et al.*, 2005; Brey *et al.*, 2017) consider parts of these aspects. Zani *et al.* (2023) conducted a CBA for different cycling interventions in complex urban environments in Zurich. They focus on the challenge of properly quantifying the costs and safety benefits of each intervention. Rich *et al.* (2021) conclude that higher usage of e-bikes leads to worse (yet still favorable) cost-benefit outcomes due to lower health benefits and higher crash costs, which are not fully compensated by higher travel time savings.

3.2.4 Representing cycling comfort

The user benefits of cycling infrastructure compared to mixed traffic can be quantified using route choice models. Meister *et al.* (2023) have estimated a recursive logit model from 4'432 cycling trajectories in Zurich. Expressing the resulting parameters in a Value of Distance (VoD) space shows the users' perception of individual route attributes in units of distance. The authors report median VoD indicators of -0.36 for bike paths and -0.66 for bike lanes. Compared to mixed traffic, using cycling infrastructure is perceived to be equivalent to reducing the distance by 36 and 66%, respectively. The authors argue that the higher valuation of bike lanes over bike paths is likely a result of forced choices in Zurich's network. In this chapter, we use the mean of the above two values for all types of cycling infrastructure: -0.51. Using the VoD indicators allows us to convert the benefits into distance and travel time that can be used in other methods, such as shortest-path routing.

Similar studies in other cities have also derived VoD indicators of cycling infrastructure relative to mixed traffic: Prato *et al.* (2018) report -0.249 for bicycle paths and lanes in peak hours in Copenhagen. Another study in Copenhagen (Jensen, 2019) shows VoD indicators of -0.044 for roads with bicycle lanes and -0.231 for roads with bicycle paths. Broach *et al.* (2012) have found 'distance values' of -10.8% to -26% in Portland, OR. Hood *et al.* (2011) report average 'marginal rates of substitution' of 0.49 (bike lanes) and 0.57 (bike paths) in San Francisco, corresponding to VoD (as defined above) of -0.51 and -0.43. Overall, the findings in Meister *et al.* (2023) in Zurich are in a similar range.

3.2.5 Preparation of street network data

Processing street networks relies on accurate and standardized data sources. OpenStreetMap (OSM) provides open geodata that is available globally in a consistent format, unlike official data, which is fragmented and often not easily accessible. As of 2017, OSM covered the entire road network in more than 40% of countries, mostly in the developed world, but including several developing nations as well. Globally, it covered 83% of all roads and was found to be superior to global datasets used by the World Bank (Barrington-Leigh and Millard-Ball, 2017). The Python package `osmnx` (Boeing, 2017) provides a convenient toolbox for extracting the data and performing basic geospatial operations. It provides a data structure for storing the street networks in a Street Graph, built on top of the `networkx` package (Hagberg *et al.*, 2008), where each street is represented as one or more edges with geometries and attributes. It also provides a set of basic simplification tools that remove most interstitial nodes (with degree=2)[1] that are not intersections and consolidate multiple nodes representing a single intersection. However, `osmnx` lacks a data structure to store the allocation of road space and determine the total road widths. Also, its embedded simplification algorithm does not provide satisfactory results in the dense urban network of Zurich.

Berg *et al.* (2022) introduce the General Modeling Network Specification[2] (GMNS) framework for storing information about traffic lanes. Originally intended for studies on autonomous driving, it is a comprehensive relational data model

1 In graph theory, the 'degree' of a node refers to the number of edges that are attached to it.

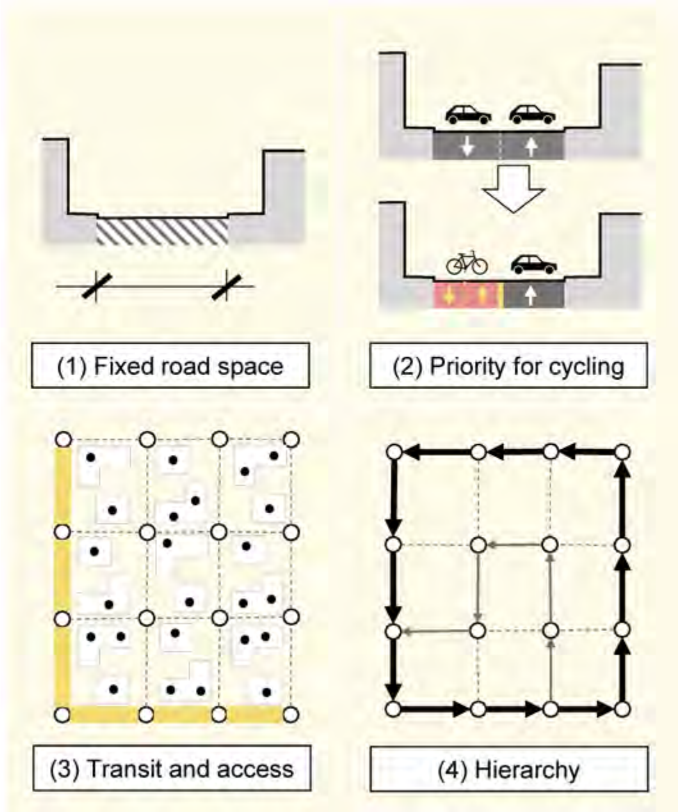
2 https://github.com/zephyr-data-specs/GMNS

with multiple tables, similar to the widely used General Transit Feed Specification (GTFS).

3.3 Conceptual approach

Based on the concept developed in Chapter 2, we model a hypothetical transformation that reallocates a large part of the road space to cycling while maintaining a high-quality public transport service and guaranteeing basic access for motorized traffic. The goal is to test the overall potential for change and illustrate the embedded trade-offs. The reallocation happens within the existing road space. No new streets are added and the pedestrian infrastructure remains unchanged. To widen the redesign possibilities, all existing traffic lanes, except those dedicated to public transport, are ignored and subject to new organization. The new distribution favors cycling to the maximum extent possible while considering the needs of other modes: Public transport must be able to operate along its given routes, and every residential location must still be reasonably reachable by motorized traffic. Finally, the resulting network must have hierarchies, where major streets channel through traffic while local streets serve only for access, similar to the "Superblocks" paradigm (Eggimann, 2022; Rueda, 2019). Figure 3.1 illustrates the design principles.

Figure 3.1: Design principles



(1) The redesign is carried out within the boundaries of the existing road space. Pedestrian infrastructure is ignored and remains unchanged. (2) The new network design favors a generous allocation of road space to cycling infrastructure. (3) The rebuilt network must enable the operation of existing public transit routes, and appropriate access to buildings by car must be ensured. (4) The resulting network must have hierarchies that channel through traffic onto main streets.

3.4 Methods

3.4.1 Nomenclature and abbreviations

The nomenclature used in this chapter is derived from four-step transportation models (Schnabel and Lohse, 2011), choice modeling (Meister *et al.*, 2023; Ben-Akiva and Lerman, 1985), and the Python libraries `networkx` and `osmnx`. Parts of the nomenclature were adjusted to avoid using the same symbols for different meanings.

3.4.2 Data acquisition

The raw street network data is acquired from OSM using `osmnx` with relevant traffic-oriented tags[3] and stored in a Street Graph (G). In addition, we use data sources specific to the context of Zurich: existing on-street parking spaces[4], a digital elevation model[5], public transport routes[6], as well as a disaggregated version of the Swiss Statistical Population (STATPOP) dataset[7], representing each permanent resident as a point. While a dig-

Table 3.1: Nomenclature

G	Street Graph
L	Lane Graph
A	Access Graph
u, v, k	Edge indices: node from, node to, key
i, j	Residential location, Parking lane
$p_{\text{req},i}$	Required parking spots at a residential location i
$p_{\text{cap},j}$	Capacity of a parking lane j
a_{ij}	Number of parking spots assigned between a residential location i and a parking lane j
s_i	Parking surplus (positive) or shortage (negative) at residential location i
n	Iteration step
$c_{uvk,mode}$	Generalized cost of traversing the edge uvk for a mode
l_{uvk}	Length of the edge uvk
VoD_x	Attribute x converted into the Value-of-Distance space
BC	Normalized Edge Betweenness Centrality
car lanes	Lanes for motorized traffic
bike lanes	Lanes for micromobility
PT lanes	Dedicated lanes for public transport
parking lanes	Lanes for on-street parking
OSM	OpenStreetMap

3 `bridge,tunnel,layer,oneway,oneway:bicycle,ref,name,highway, maxspeed,service,access,area,landuse,width,est_width,junction, surface,lanes,lanes:forward,lanes:backward,cycleway,cycleway: both,cycleway:left,cycleway:right,bicycle,bicycle:conditional, sidewalk,sidewalk:left,sidewalk:right,foot,psv,bus,bus:lanes, bus:lanes:forward,bus:lanes:backward,vehicle:lanes:backward, vehicle:lanes:forward,busway,busway:right,busway:left,footway`

4 `https://data.stadt-zuerich.ch/dataset/geo_oeffentlich_zugaengliche_strassenparkplaetze_ogd`

5 `https://www.swisstopo.admin.ch/en/height-model-swissalti3d`

6 `https://data.stadt-zuerich.ch/dataset/ktzh_linien_des_oeffentlichen_verkehrs__ogd_`

7 `https://www.bfs.admin.ch/bfs/de/home/statistiken/bevoelkerung/erhebungen/statpop.html`

ital elevation model is available globally[8], the other datasets may not be available for the given context. However, enriching the data model with these sources is optional, and the process can be run without them, with the following limitations: Without a public transport routes dataset, the resulting network may conflict with the existing routes. Without an on-street parking dataset, any potential of repurposing space through a reorganization of on-street parking would be ignored. Without a population dataset, parking cannot be redistributed accurately based on nearby residents. Finally, in places with less detailed road tags, e.g., the number of lanes, the resulting street network will have less accurate road widths, thus having a lower accuracy in representing the road space usage potentials. Nevertheless, even with these limitations, users may still produce at least a proof of concept. They may distribute parking based on other data such as building footprints or business locations. For public transport routes, users may rely on relations in OSM (if available) or digitize the routes manually.

3.4.3 Data model and preparation

The primary data structure is an extended version of the directed Street Graph (G) from `osmnx`. In addition to the original format, each edge is extended with an attribute that contains a representation of its lanes, with a simplified data structure adopted from the GMNS format. For representing the lanes in a human-readable format, we use the following encoding: `[lane type][direction][status (optional)][width (optional)]`. Possible lane types are `M` (car lane), `L` (bike lane), `H` (highway lane), `T` (PT lane), `R` (parking lane), and `X` (mixed cycling and pedestrian path). Possible directions (relative to the directed edge) are `<` (backward), `>` (forward), `-` (both directions), and `?` (to be defined in the redesign process). The status represents whether the lane is already final or yet to be edited. It can have the values `*` (fixed), `/` (optional), or `!` (to be determined by an algorithm). The `?` direction, as well as the `/` and `!` status, are used throughout the rebuilding process (see Section 3.4.8) to keep track of lanes that can still be removed or changed, and those that cannot be altered anymore. Outside the rebuilding process, all lanes have a `*` (fixed) status and a set direction. The last position, the width, is in the units of the projection used, typically in meters. If the status and width are missing, we assume the lane to be fixed and have the default width. The lanes are separated by `|` to represent the entire road space allocation on the street. As an example, `L<*2.5 | T<*3 | M>*3 | L>*2.5` represents a street with two separated 2.5-meter cycling paths (one backward and one forward), a dedicated PT lane in the backward direction, and a regular car lane in the forward direction. It is a string representation of the object-oriented data structure in Python, that can be easily viewed and edited in GIS software.

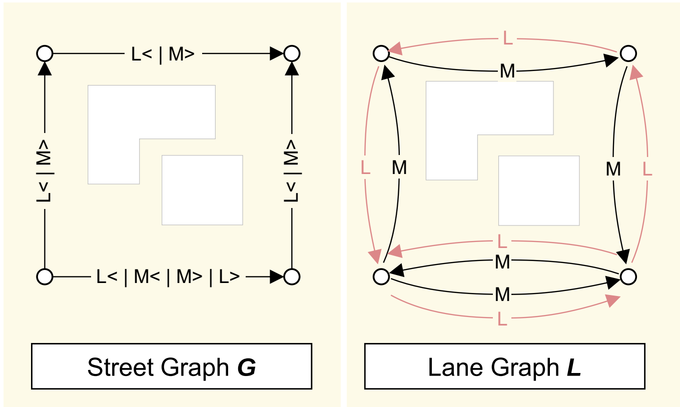
Default lane widths used in this work were measured on satellite images of existing streets in Zurich: 3.0m for standard car lanes, 4.5m for short bidirectional car lanes on residential streets, 1.5m (half of a car lane) for standard cycling lanes, 2.5m for mixed pedestrian and cycling tracks, and 2m for parking lanes. During the rebuilding process, the preferred cycling infrastructure consists of two lanes per direction, thus resulting in a width of three meters if the available space permits.

8 For example, the US SRTM dataset: `https://doi.org/10.5066/F7PR7TFT`

The initial lanes are reconstructed based on tags from OSM. Since there is no information about the actual lane widths in OSM, we use the default values described above. The total width of every road is determined by the sum of its lane widths. The OSM tags are used as follows: The highway tag provides information about road hierarchies, lanes shows the number of car lanes and dedicated PT lanes, oneway defines the directionality of the lanes, psv represents access by public transport and service vehicles, and maxspeed provides the maximum speed. On some roads, vehicle:lanes:forward, vehicle:lanes:backward, bus:lanes:forward, and bus:lanes:backward provide explicit information about the order and directions of car- and PT lanes. Otherwise, it is implied from the previously mentioned tags. Finally, bicycle defines the usability of roads and paths by cyclists, e.g., pedestrian paths with cycling allowed, and the tags cycleway:left, cycleway:both, and cycleway:right, are a source of information about the presence and type of cycling infrastructure. For the exact implementation, refer to the source code. [9]

For routing and calculation of graph measures using standard tools in the `networkx` library, we convert G to a Lane Graph (L) – a secondary representation where each lane is a separate directed edge, with cost attributes for each mode. L offers the benefit of being routable, but in contrast to G, it introduces a redundancy of multiple edges representing the same physical street axis. Therefore, we continue to use G as a primary data structure and convert to L (and back to G) only for those steps where it is needed. Figure 3.2 illustrates the difference between these two data structures.

Figure 3.2: Network data structures



The primary data structure, a Street Graph (G), represents every street by one directed edge and a set of lanes, each with a type and direction relative to its edge. A secondary data structure, the Lane Graph (L), represents every lane by a separate directed edge, thus allowing routing and calculation of graph measures.

9 `snman/space_allocation.py/_generate_lanes_for_edge()`

3.4.4 Simplification

Next, we simplify the network acquired from OSM such that every street section between intersections is represented by one edge and every intersection by one node. Before the simplification, the largest intersections in Zurich have up to ~100 nodes, and some streets are represented by 2-5 parallel edges. The process is an extension of the simplification provided by `osmnx`, and is described in the next paragraphs. Figure 3.3 illustrates the difference between the original and the simplified network using the two algorithms.

The existing simplification tools in `osmnx` provide two steps: Eliminating (some) interstitial nodes with degree=2, and merging complex intersections. The nodes in intersections are merged using a combination of geometric buffers and weakly connected components. A buffer with a globally defined radius is added around every point, and all touching buffers are merged. Within each resulting geometry, all nodes are sorted into weakly connected components (WCC)[10], and those in the same WCC are merged into one node. Its location is the center of gravity of the original node geometries.

However, this approach has several shortcomings that are crucial for the network in Zurich: First, overall, it is focused solely on edges and does not consider their allocation of road space. Thus, the merged edges only maintain their tags as lists of original values, but there is no data structure for managing lanes when edges are merged or separated. Second, it fails to merge all parallel edges and does not distinguish between those representing the same street and physically separated parallel streets. Third, its strict WCC condition in merging intersections does not allow proper treatment of wide streets with multiple parallel edges where side streets are often attached only to some of the main street edges. Fourth, it does not allow the exclusion of certain streets from the simplification process, such as highways, where complex interchanges are difficult to simplify properly without losing important information. Finally, the process does not provide a way to manually correct the intersection extents in cases where the algorithm fails to provide satisfactory results. To overcome these limitations, we add the following extensions to the process.

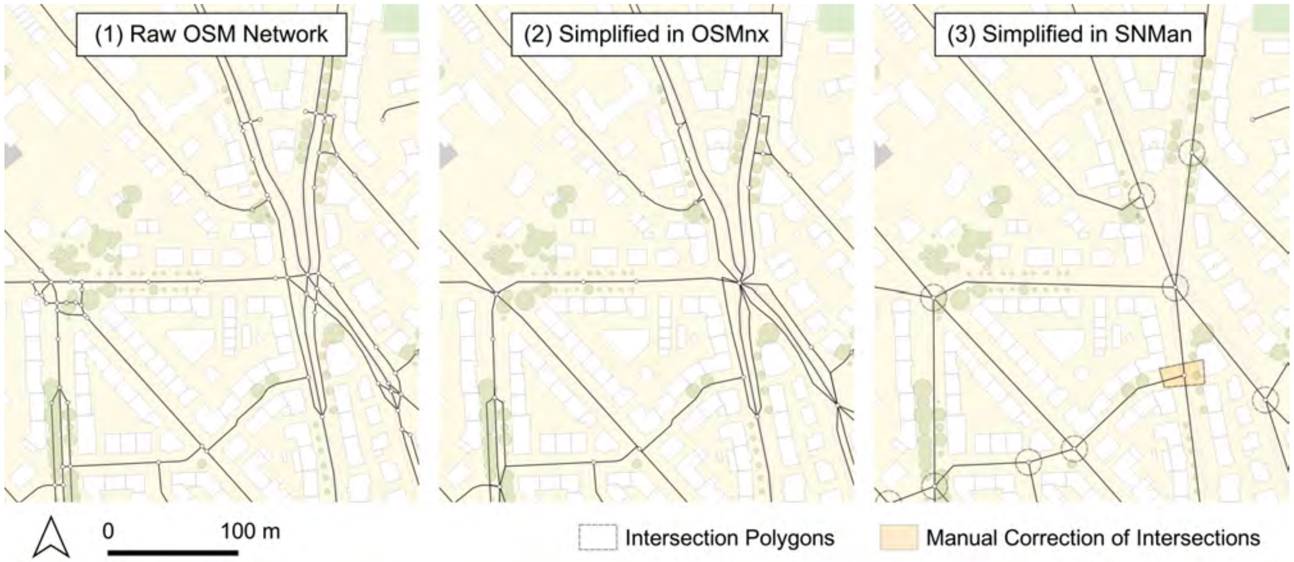
First, we extend the process for merging consecutive and parallel edges by a logic that maintains the consistency of the road space allocation data. Whenever parallel edges are merged, their lane lists are merged as well. When consecutive edges are merged, the lanes of the longest one are kept, and all other lane lists are discarded. Similarly, we add a logic for treating the tags, maintaining the highest value (e.g., highest maxspeed or highest highway tag), rather than storing all values in lists.

Second, we use Hausdorff Distance[11] (HD) to distinguish between parallel edges of the same street and parallel streets. If the HD of two parallel edges is more than 30 m, they are not merged, even if they share the same pair of nodes. This allows to keep parallel streets separated, instead of merging them and creating streets with an unrealistically high number of lanes, which would otherwise happen in residential areas of Zurich.

10 A 'weakly connected component' is a set of nodes in a directed graph where a path exists between any two of them. All edges can be passed in both directions, unlike a "strongly connected component," where each edge can only be passed in its direction.

11 Hausdorff Distance refers to the longest distance between any point along the geometry of street X and its closest counterpart on street Y, originally defined in Hausdorff (1914)

Figure 3.3: Comparison of network simplification algorithms



Map extent around Schaffhauserplatz in Zurich: (1) Raw network extracted from OSM, with interstital nodes removed using osmnx. (2) After consolidating intersections in `osmnx`. (3) After using the snman simplification process.

We also run the entire simplification process multiple times to catch all merging opportunities that arise from the later steps. Third, we add two steps for properly merging intersections on large streets with multiple parallel edges. In one step, we add an interstitial node to each edge passing through an intersection polygon if both of its endpoints lay outside of the polygon. In the other step, we create artificial connections between the nodes within intersections if they are at the same physical level (based on the layer tags of their adjacent edges). This modification avoids splitting the intersections on major streets into multiple nodes and thus allows also to properly merge all of their parallel edges into one.

Fourth, we add a possibility to exclude some nodes and edges from the simplification.

Fifth, we modify the intersection merging process by adding a manual override of the automatically determined intersections. We take a polygon layer input and superimpose its features onto the automatically detected intersection polygons. This way, manual corrections are possible in cases where the simplification is not satisfactory and can be applied automatically to every network generated in the future.

Lastly, we create an iterative process consisting of the original `osmnx` functionalities and the extensions introduced above. The topology simplification is repeated multiple times to catch any secondary simplification potentials that appear later:

1. Topology simplification, run three times:
   - 1.1. Label each node and edge whether it should be left unchanged during the simplification process.
   - 1.2. Create the intersection geometries using a buffer of 10 meters, as typically used in literature (Barrington-Leigh and Millard-Ball, 2020; Boeing, 2022), superimposed by a layer of manually drawn polygons.
   - 1.3. Split edges passing through intersection polygons.
   - 1.4. Add connections between intersection nodes on the same physical level.
   - 1.5. Consolidate intersections using the previously generated polygons.
   - 1.6. Merge consecutive edges.
   - 1.7. Merge parallel edges.
2. Simplify the edge geometries.
3. Remove all nodes and edges outside of the largest WCC.

3.4.5 Enrichment

Next, we enrich the Street Graph G with additional data sources. We extend the node attributes with elevation data and calculate a grade value for each edge. We match public transport routes to the street network using Leuven Map Matching (Meert and Verbeke, 2018). Similarly, we match individual parking spaces provided by the official datasets to their respective streets and convert their counts to an approximate number of parking lanes.

3.4.6 Representing the comfort of cycling

Since reallocating road space to dedicated cycling infrastructure impacts cyclists mainly through comfort, the resulting change in generalized cost must be represented in the shortest path calculations. For that, we adjust the corresponding cost $c_{uvk,\text{cycling}}$ using the VoD indicators estimated in Meister *et al.* (2023), such that:

$$c_{uvk,\text{cycling}} = l_{uvk} * [1 + VoD_{\text{infra}}(\text{infra}_{uvk}) + \text{VoD}_{\text{grade}}(\text{grade}_{uvk})] \tag{3.1}$$

For $\text{VoD}_{\text{infra}}$, we assume -0.51 if dedicated cycling infrastructure is present and 0 otherwise. $\text{VoD}_{\text{grade}}$ is 0.55 for $2\% < \text{grade} \leq 6\%$, 3.11 for $6\% < \text{grade} \leq 10\%$ and 4.33 for $10\% < \text{grade}$. Cyclists can use general travel lanes but the link cost is lower on cycling lanes. On the other hand, motorized traffic cannot use cycling lanes.

Car trips are affected primarily by the detour length. VoD Indicators for driving comfort would be theoretically possible, but we leave them out for the sake of focus and simplicity. For car trips, the cost of each link is equal to its length:

$$c_{uvk,\text{car}} = l_{uvk} \tag{3.2}$$

Other comfort-related aspects, such as additional stops or turns, are ignored for both cycling and car trips. Travel time changes due to congestion would need to be evaluated using an assignment model. For comparability of the resulting average shortest paths in Section 3.5.3, we report the values with and without VoD indicators.

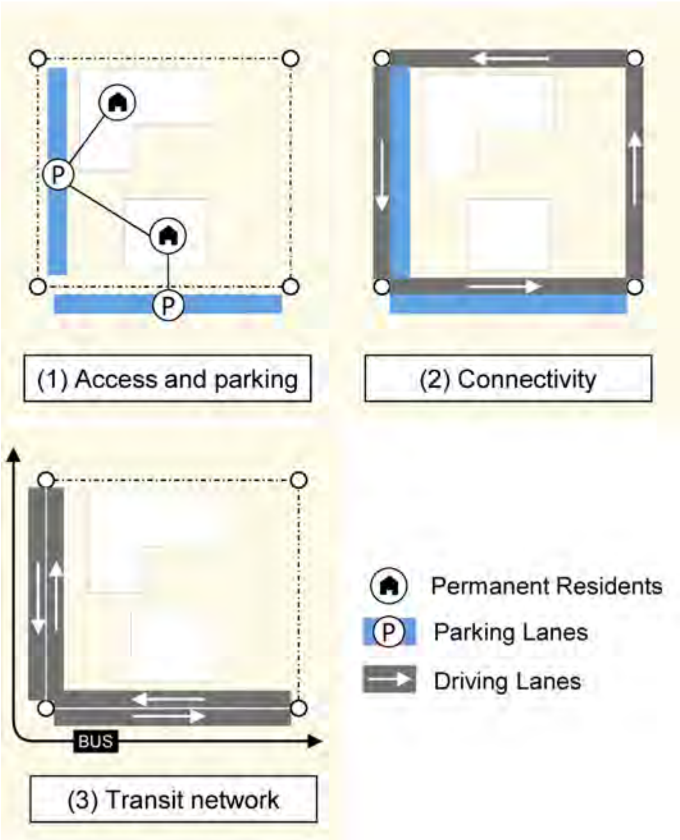
3.4.7 Network constraints

To guarantee network connectivity, ensure sufficient access to buildings by cars, and maintain a high quality of public transport, we enforce three constraints throughout the rebuilding process: (1) Every residential location must obtain a guaranteed number of on-street parking or loading spaces within a given distance. (2) The network cannot be disconnected, with two sub-conditions: (2a) All parking spots must be accessible by having a parallel car lane on the same street, and (2b) The number of strongly connected components[12] cannot increase. This means that we cannot remove a car lane if it would increase the number of isolated car lane networks and nodes with no car access. And, finally, (3) the network must allow the operation of all existing public transport routes (except minor neighborhood and night-time services). Figure 3.4 illustrates the constraints.

The access to residential locations is ensured using an Access Graph (A). It establishes a connection between each pair of residential location i and on-street parking lane j within a given radius. Every residential location has a defined number of required parking spots $p_{\text{req},i}$, based on its number of residents. On the other hand, each parking lane has an estimated capacity $p_{\text{cap},j}$ based on its length. To keep track of under- or overprovision of parking spots, we use a gravity model of traffic distribution (Schnabel and Lohse, 2011) to assign the number of parking spots a_{ij} for every pair of a residential location and a parking lane. The same process can be used for commer-

12 The "number of strongly connected components" represents the number of subnetworks that are disconnected from each other. Refer to footnote 10 for "strong" and "weak" connectivity

Figure 3.4: Constraints during the rebuilding process



(1) Every residential location must have access to a sufficient parking supply assigned to it within a given radius. (2) All parking lanes must be accessible by car. (3) Streets with public transport routes must allow passage in each direction of each route.

cial locations as well. The gravity model is fixed at the side of the parking lanes, thus concentrating any surplus or shortage of parking at the side of the residential locations (e.g., positive means that residents at location i have more parking than necessary):

$$s_i = \sum_j a_{ij} - p_{\mathrm{req},i} \tag{3.3}$$

In each step n of the rebuilding process, parking lanes can only be removed if the sum of all instances of parking shortage (where $s_i < 0$) does not increase:

$$\sum_i \min(s_{i,n+1}, 0) \leq \sum_i \min(s_{i,n}, 0) \tag{3.4}$$

To *maintain connectivity*, we enforce two conditions: First, all nodes of the graph must be strongly connected for cyclists. Second, all parking lanes must have at least one parallel car lane for access, and this car lane must be part of a strongly connected graph for cars. Each car or cycling lane can only be removed if none of these conditions are violated.

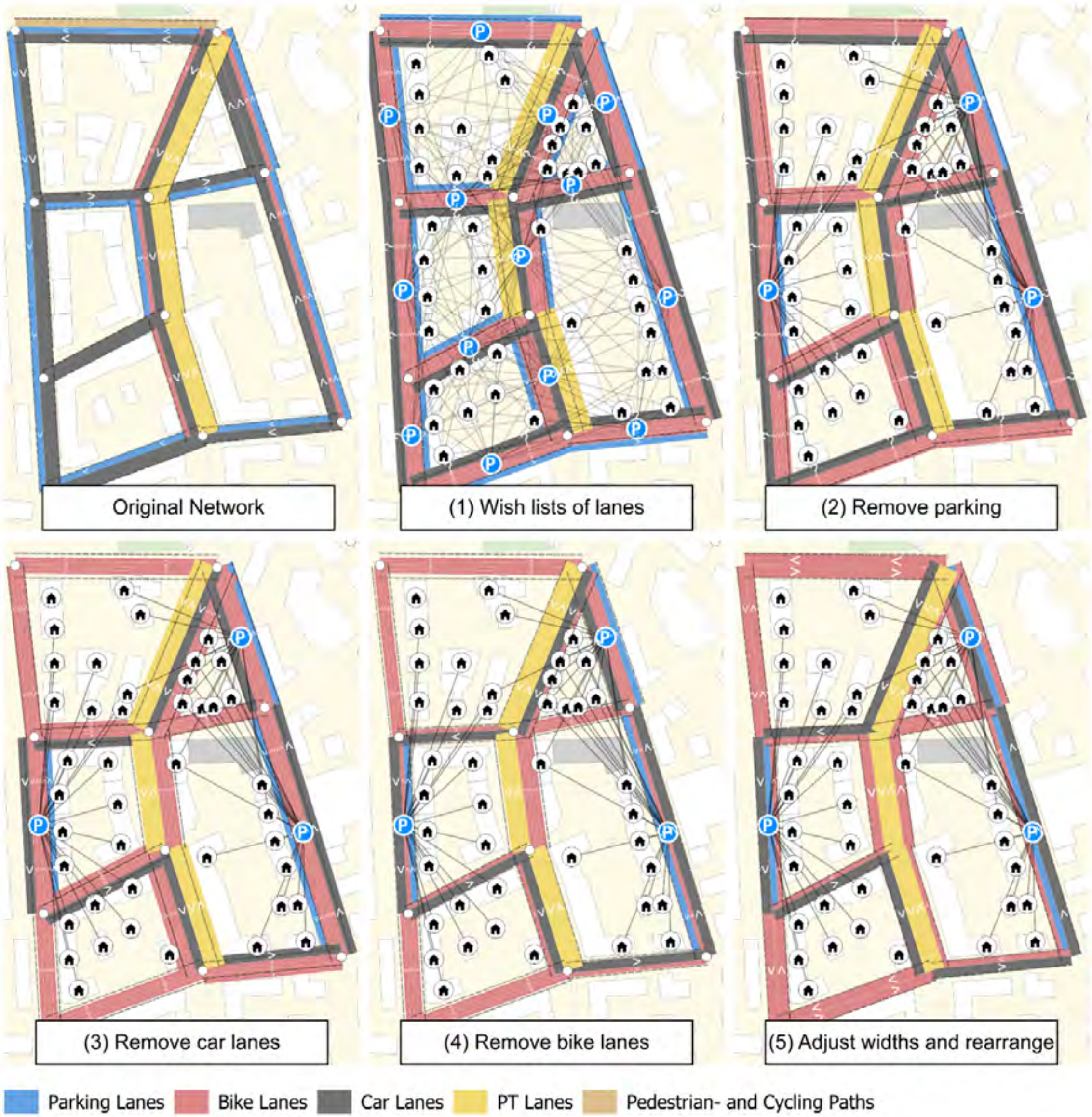
To *maintain the operation of public transport*, every street with tram or bus routes must allow their passage in each route direction. Removal of travel lanes is only allowed if it does not lead to a violation of this condition.

3.4.8 Network design

We apply a reversed network formation process, adapted from Steinacker *et al.* (2022), following the "betweenness-bottom-up (car)" approach discussed in 3.2.1. It provides a similar performance as the mathematical optimization proposed by Wiedemann *et al.* (2025) while enabling a flexible implementation that can be easily extended with further heuristics to cover practical needs in real-life environments.

The process consists of five steps: First, we (1) generate complete ”wish lists” of lanes for all streets. Then, we perform the following reduction steps until the total width of the assigned lanes on each street does not exceed its available width: (2) removing parking lanes, (3) removing car lanes, (4) removing bike lanes, and (5) adjusting lane widths to fill the available street width. Figure 3.5 illustrates the steps on a small street network. The process is carried out on a Lane Graph. Thus, when referring to ”lanes”, we also refer to their corresponding edges in the Lane Graph. The resulting Lane Graph is then converted back to a Street Graph to maintain the primary data structure. In the following paragraphs, we describe the algorithms used in each step.

Figure 3.5: Five steps of the network redesign process



(1) Assign a wish list of desired lanes to every street. (2) Remove parking lanes as long as the minimum parking provision for every residential location is satisfied. (3) Remove car lanes as long as the network connectivity and passability for public transport are fulfilled. (4) Remove bike lanes that exceed the available road space width. (5) Merge same-direction cycling lanes, adjust lane widths to fill out any spare road space, and rearrange the overall order of lanes.

The wish lists of lanes are generated such that every street provides the most desirable travel options for every mode in each direction: One car lane, two bike lanes (for a comfortable double width), and a lane for on-street parking. Depending on the planner's aims, the wish lists can be set differently for each road hierarchy, and each lane in the wish list can be either fixed (not removable throughout the later steps) or optional. Similarly, the lane widths can be set differently for each road hierarchy or depending on the maximum speed. Simultaneously, we construct an Access Graph, connecting residential locations with suitable parking lanes, as described in Section 3.4.7.

Second, we remove parking lanes as long as the necessary parking provision is not violated. We follow the order of largest excess width (the difference between available street width and the sum of lane widths). All parking lanes whose removal would violate the constraints in Section 3.4.7 are marked as fixed, and the algorithm is finished once all parking lanes are fixed.

Third, we remove car lanes, following the order of their normalized edge betweenness centrality[13] (BC). Removing those with the lowest BC first results in permeable networks that favor smaller detours for the through traffic, while using the opposite order creates less permeability. Like in the previous step, lanes whose removal would violate any of the constraints are marked as fixed. The algorithm is finished once all car lanes are fixed.

Fourth, we remove bike lanes on all streets whose allocation still exceeds the available width. The order in which individual bike lanes along a street are removed is controlled by minimizing the increase in cycling cost between its nodes (sum of cost differences in both directions). With this logic, one-way streets for car traffic will favor contraflow cycling facilities.

13 A measure for the importance of an edge: Number of shortest paths in a graph passing through the given edge, normalized by the overall graph size. We use the implementation in `networkx.edge_betweenness_centrality()`

Finally, the lane widths are adjusted such that they fill out any spare street width after the removal of lanes with discrete widths. On streets with bike lanes, the spare width is filled out by widening them. In other cases, all other lanes are widened proportionally. Same-direction cycling lanes are consolidated into wider paths, and all lanes are rearranged according to a pre-defined order.

3.4.9 Customization

The process described above is implemented such that users can generate a vast variety of custom designs. Individual steps can be reordered, their inputs can be replaced, or custom algorithms can be provided for individual steps. The process can be run in steps, for individual parts of the network separately, each with a different design configuration – allowing to combine multiple design strategies in the same resulting network. Users may also match polylines with manual overrides of the existing road space allocations onto the network or impose specific future road space allocation on individual streets during the redesign process. The functions for creating the lane with lists, as well as for carrying out the lane removal, can be replaced by custom implementations. Table 3.3 shows an overview of user inputs that can be used for customizing the designs. See Section 3.5 for an exemplary application to Zurich.

3.5 Case study in Zurich

3.5.1 Description

As of 2024, the City of Zurich, Switzerland, had a population of 443'037 inhabitants, an area of 91.9 km², and roughly 1.9 million inhabitants living within its entire metropolitan region (City of Zurich, 2024c). The number of registered cars was

Table 3.3: Possible user inputs for generating different designs

Input	**Values**	**Design outcomes**
Rebuilding regions	Custom polygons, to be applied in a given order	Network hierarchies and neighborhoods with different design rules
Street hierarchies to include	highways, main roads, local roads	All or only some street hierarchies are included in the rebuilding process
Street hierarchies to fix	Highways, main roads, local roads	Some street hierarchies are left unchanged
Parking mode	By need (by gravity model), as existing, or no parking	On-street parking is allocated according to the given mode
Parking needs	Walking radius and maximum number of residents per parking spot	Number of resulting on-street parking spaces in the parking mode "by need"
Public transport mode	PT lanes along every PT route (mandatory or optional), PT lanes as existing, or no PT lanes	PT lanes are allocated according to the given mode
Car lanes mode	Separated by direction or bidirectional	Types of resulting car lanes
Order of car lane elimination	Lowest BC or highest BC	Permeability or "Superblocks"
Custom function for generating the lane wish lists	A function.	Desired allocation of space on every street
Custom functions for eliminating parking, car lanes, and bike lanes	Functions.	Custom optimization for different network structures, travel times, access, etc.
Custom overrides of lane wish lists on individual streets	Polylines with the desired wish lists	The resulting design may have specific lanes on some edges, while the rest of the network is arranged automatically, according to the constraints.

134'601 and has remained nearly constant since 2002 (City of Zurich, 2024b), while car ownership decreased from 388 to 318 cars per 1'000 residents (City of Zurich, 2024a). Its relatively narrow streets and high density of PT services pose heavy restrictions on the construction of cycling facilities. Additionally, the cantonal constitution currently limits any measures that would reduce the capacity of cantonal roads, which entail a large portion of major streets within the city. In this case study, we apply the process presented above to propose a network-wide reorganization of road space allocation in favor of cycling. We consider the functional constraints related to public transport and access but ignore the current legal restrictions.

3.5.2 Design considerations and process

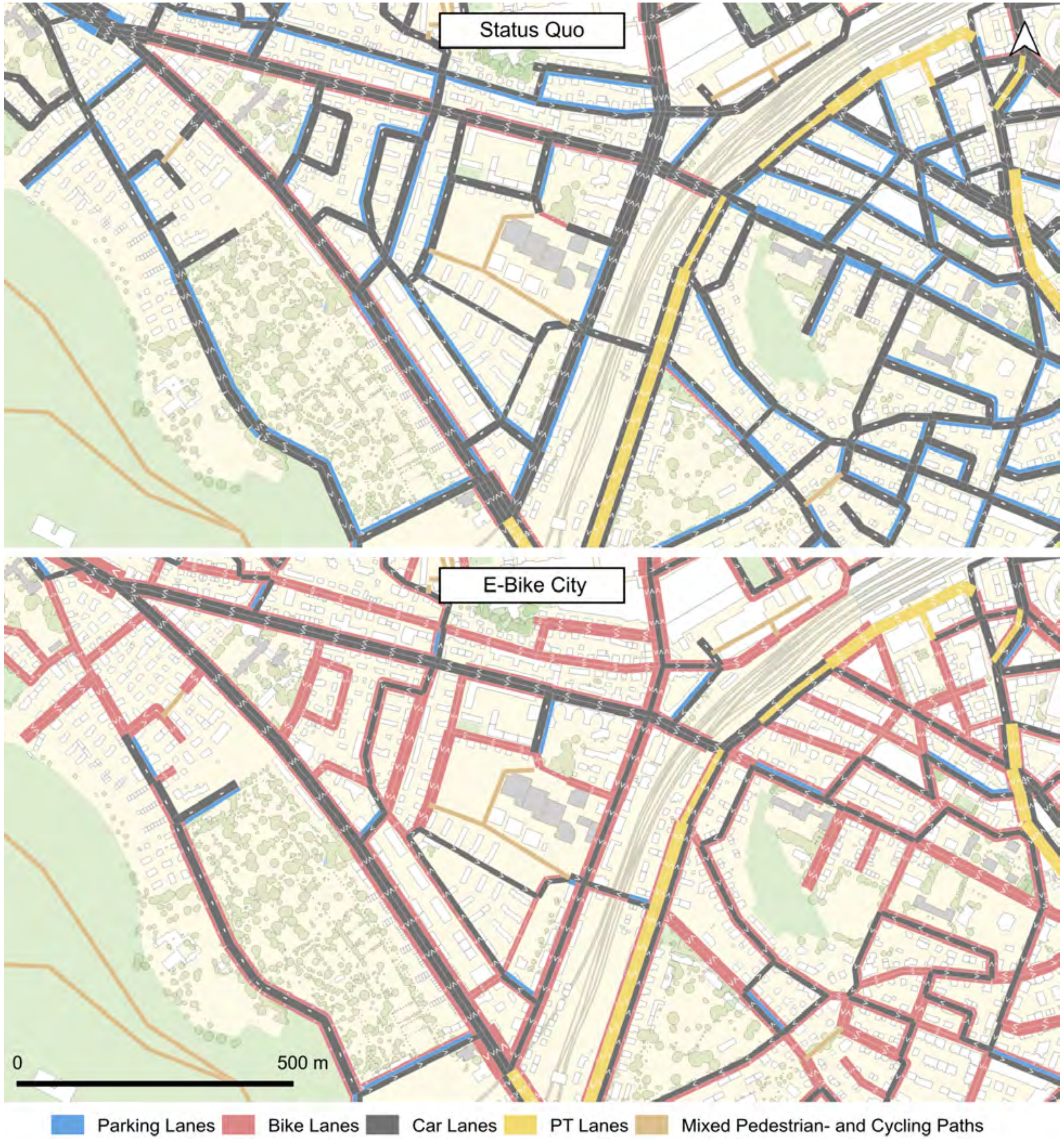
The redesigned network should substantially increase the length and width of cycling facilities while maintaining the quality of public transport and guaranteeing basic car access for every residential location. Further, car traffic should be concentrated on a network of main streets while minimizing the traffic volumes in residential areas. On-street parking facilities should be reduced mainly to short-term loading zones and parking for the disabled. Access to parking spaces should be guaranteed within a similar walking distance as public transport stops.

The transport network, after simplification, has approximately 5'000 nodes and 7'000 edges within the municipal area of Zurich. To maintain a hierarchy of permeable main streets and low-traffic neighborhoods, we partition the network into one region with all main streets (OSM highway tags primary, secondary, and tertiary) and 60 neighborhoods between the main streets. All motorways are ignored and left unchanged. For the main streets, we prioritize the removal of car lanes by lowest betweenness centrality, while for the neighborhoods, we do the opposite to discourage the through traffic. In all regions, we fix the existing PT lanes but let all other lanes be determined by the process. We provide basic car access, with at least one parking spot per 60 residents within a radius of 200 meters from each residential location. This is roughly one-sixth compared to today's number of parking spaces (46'282 parking spaces, 9.6 residents per space). However, we have ignored any parking spaces on private grounds and in large garages. Thus, the effective proportion of parking spaces removed is substantially smaller. For simplicity, we focus on residents as users of the parking spaces and ignore the other groups (e.g., businesses, tourists, etc.). The radius of 200 meters is similar to the typical maximum. crow-fly distance to public transport stops.

3.5.3 Results

The run time was 7 h 39 min on an 11th generation Intel Core i7 processor without parallelization. Figure 3.6 shows a comparison of the network before and after rebuilding. Table 3.4 shows the resulting metrics for all streets within the city of Zurich, except highways and pedestrian infrastructure.

Figure 3.6: Network previews



The road space has been substantially reallocated, increasing the share of cycling infrastructure by a factor of 4.5, from 12.1% to 54.3%. On the other hand, the proportion of space for general travel lanes has decreased by almost one-half, from 66.6% to 35.1%. The space for on-street parking was reduced by more than two-thirds, from 14.3% to 3.8%. In alignment with the original design goal to maintain the quality of public transport, the space allocated to PT lanes has remained unchanged. The total road space grew slightly. This is due to a shortcoming of the reversed network generation process that, in some cases, results in bidirectional car traffic (and larger total lane width) on today's one-way residential streets.

The cost of the average shortest path for cyclists (considering the VoD indicators for comfort and grades) has decreased by 24.1%. Without considering the VoD indicators, the average shortest path remained nearly unchanged which can be explained by a high permeability of the current Zurich's network, allowing cyclists to use almost all links in both directions. The reconfiguration does not make cycling trips substantially shorter, but it reduces their generalized cost through higher comfort. On the other hand, the average shortest path for cars increased by 35.7%, as a result of the many one-way and cycling-only streets.

The normalized average betweenness centrality grew by 157.5% for cars and decreased by 3.5% for bicycles. According to the model by Loder et al. (2019), both the decreased total lane area (proportional to total lane length) and the increased betweenness centrality lead to lower network capacity for cars. On the other hand, slightly lower betweenness centrality and more road space usable by cyclists increases the capacity for this mode. However, accurate statements about the overall capacity change can only be made with a traffic simulation.

3.5.4 Plausibility checks and violations

The rebuilding process was developed iteratively, with several rounds of manual plausibility checks. These included the resulting road typologies, shortest paths between important origin/destination pairs, and violations of the design constraints (street widths, parking access, connectivity, and public transport). Most design issues could be resolved by adjusting the algorithms, changing the user inputs (see Table 1), manually resolving simplification errors in the network, or correcting errors in the OSM data. However, two issues have not been resolved yet: First, one-way streets are occasionally converted to two-way traffic despite missing space, and second, the routing of car lanes through the neighborhoods results in implausible detours in some cases. Nevertheless, the extent of the width violations is relatively small (2.4% of the total road space) and has little practical relevance: It applies mainly to residential streets, usually with short lengths and low traffic volumes, so bidirectional traffic is possible even with smaller-than-usual widths. Similarly, improving the implausible routing of car lanes through neighborhoods would make the automatically generated network plan more visually appealing but would have little impact on the results presented in this chapter or a future impact assessment. In any case, any plans for actual implementation must be scrutinized and improved with manual adjustments if necessary.

3.6 Discussion

The results show that a substantial reallocation of road space to cycling infrastructure is possible while still providing a connected network for other modes. Essential car trips are still possible, although with detours and longer access and egress distances. The remaining on-street parking spaces, centralized at

Table 3.4: Network indicators

Metric			Status Quo		E-Bike City	Change
avg shortest path for cars	km		5.463		7.412	+35.7%
avg shortest path for bicycles	km		5.391		5.334	-1.1%
avg shortest path for bicycles with VoD indicators	km		4.824		3.661	-24.1%
avg normalized betweenness centrality for cars	-		0.00506		0.01303	+157.5%
avg normalized betweenness centrality for bicycles	-		0.00367		0.00354	-3.5%
road space general travel lanes	km^2	(66.6%)	3.7564	(35.1%)	2.0257	-46.1%
road space parking	km^2	(14.3%)	0.8040	(3.8%)	0.2188	-72.8%
road space PT lanes	km^2	(7.0%)	0.3962	(6.9%)	0.3962	+0.0%
road space cycling infrastructure	km^2	(12.1%)	0.6816	(54.3%)	3.1340	+359.8%
total road space	km^2		5.6382		5.7747	+2.4%

a few locations in every neighborhood, still provide space for short-term loading, pick-up, and drop-off, as well as parking for persons with disabilities. Personal electric vehicles, such as e-wheelchairs or electric carts, may help to overcome the last couple of hundred meters for deliveries or for those who are unable to walk. An appropriate design of the cycling infrastructure would allow unchanged access for emergency and utility vehicles. However, the transformation is only possible with a substantial reduction of capacity and parking for motorized traffic, as well as a redefinition of the minimal access standard to buildings by cars. For such a future to be viable, the small modes, together with public transport, must be attractive enough to trigger a substantial decrease in car ownership.

The network design produced for Zurich decreased the perceived travel time for cyclists by 24.1% but increased the travel time for drivers by 35.7%. This contrasts the much more optimistic Pareto frontiers reported in Wiedemann *et al.* (2025), showing that the same increase in car travel time would reduce the perceived travel time of cyclists by roughly 45%. However, the difference can be explained by the fact that this case study considered further design constraints, such as public transport, network hierarchies, and on-street parking. Moreover, the metrics don't consider the benefits of wider cycling paths on road sections that already have narrow cycling lanes, but they include the detours to car traffic that result from such reallocation of road space.

We have considered many real-world needs, but some aspects have still been left out. First, we have not made any changes to the pedestrian spaces. Second, the parking provision was controlled by only rudimentary assumptions about the maximum number of residents per parking spot, as well as the maximum distance from every address. Third, in the assessment, we have considered the VoD indicators only for cyclists and neglected any changes in speed and comfort for drivers. Lastly, the simplification has removed detailed information about the intersections, such as the available infrastructure or turn restrictions.

3.7 Conclusions and further work

While the accessibility growth in the last seventy years was driven mainly by adding large infrastructures, in this chapter, we have turned the attention to merely reorganizing the usage of existing streets. The process we have introduced enables researchers and planners to quickly test alternative urban mobility paradigms at any scale, from closing down a neighborhood street to reorganizing road space in entire cities. The outputs can serve as starting points for discussions about future urban transport policies. Together with appropriate metrics, they may help illustrate and quantify key trade-offs, such as the one between the provision of convenient on-street parking, the perceived cost of cycling, and dedicated bus lanes. Planners and communities can work on top of these outputs to create final designs, adding all local details that have not been considered in the automated process, such as exact street and intersection designs, detailed access needs of individual buildings, or rerouting public transport services.

Future work should focus on two directions: Improving the design and assessing the impacts. The first and most important improvement should integrate mathematical optimization (Wiedemann *et al.*, 2025) and cost-benefit analyses (Rich *et al.*, 2021; Paulsen and Rich, 2023; Zani *et al.*, 2023) in the design process to deliver results with better overall performance and a consideration of goals that is consistent with economic theory. Second, it should include aspects beyond mere traffic considerations, such as pedestrian spaces, mitigation of urban heat, or stormwater resilience by allocating parts of the street space to a wider set of functions. Such an extension would also need to consider ways of increasing the level of detail in the network data, as well as improving the simplification algorithm to deal with the complexities of pedestrian networks. Third, future work may improve the data and assumptions used for the provision of parking, such that the needs of businesses or residents in neighborhoods with different parking alternatives are also considered. Also, the provision of bicycle parking at major destinations should be considered. Fourth, further development of the simplification process may retain more information about infrastructure in intersections that is currently lost. And, finally, the design process should also consider transition aspects, with the possibility to generate intermediate stages of implementation.

On the impact assessment side, future work should build a comprehensive traffic simulation for the proposed scenario. In (Ballo *et al.*, 2025), we show the first steps toward an agent-based traffic simulation and accessibility analysis that shows the changes for different population groups. Further work should also focus on a CBA to create a closed end-to-end process, starting with different network design concepts and ending with easily comparable CBA metrics. Other future work may also refine parts of the assessment process, with VoD and travel time metrics for different bicycle types, cycling facility variants, and cars.

In summary, we have contributed to a discussion about future transport policy directions by introducing a process to quickly envision different city-wide road space allocation schemes. We hope it will inspire fellow researchers and policymakers to explore the potential and implications of projects that merely reallocate road space instead of building new infrastructures.

Software and data availability

The latest version of the `snman` (Street Network Manipulator) software introduced in this chapter is available open-source: `https://github.com/lukasballo/snman`. The exact code, together with the datasets used, is available here: `https://zenodo.org/doi/10.5281/zenodo.13621694`.

Chapter 4: Design of Streets and Intersections

This chapter is based on design workshops conducted in 2023/2024 jointly with Matias Cardoso, drawing on feedback from Thomas Hug, Catherine Eliott, Kay Axhausen, and others (see acknowledgments at the beginning of this thesis for a complete list). The individual contribution of Lukas Ballo was the conceptualization and writing of the manuscript. Matias Cardoso provided the background research on street and intersection types and drafted the designs. The professional visualizations were created by Nightnurse Images AG.

The visualizations were supported by an EnergieSchweiz grant from the Swiss Federal Office of Energy (SFOE Contract Number SH/8100405-02-02-04)

4.1 Introduction

This chapter advances the principles of street and intersection design in an E-Bike City while adhering to functional and network-wide constraints. It aims to illustrate how such a city would function and how its facilities would look and feel. The designs presented here are the outcome of a year-long design workshop conducted in 2023/2024, evolving from initial sketches and expert discussions into CAD drawings and professional visualizations.

Subjective safety is crucial in promoting widespread cycling adoption (Geller, 2009). Cycling infrastructure in Switzerland, built according to existing practice, is often perceived as stressful and unsafe (Pfändler, 2023). Currently, proposed approaches of expanding cycling lanes and traffic calming compete with other important needs, such as maintaining high speeds of public transport (Ledebur, 2022b; Forster, 2023) or access through on-street parking (Ledebur, 2022a). Moreover, growing volumes of cycling traffic on the present infrastructure exacerbate conflicts between cyclists and pedestrians (Aschwanden, 2023).

Public discussions reflected in hundreds of reader comments on press reports covering our work (e.g., Vogt (2024); Aeberli (2023); Gut (2024); Vogt (2023); Laukenmann (2022)) highlight the ongoing challenge of balancing improved cycling infrastructure with accessibility for motorized traffic (Elliot *et al.*, 2024). A particular area of concern is the impact on access for the disabled and for contractors (Ledebur, 2022a).

4.2 Related norms and similar work

Roadway design in Switzerland is guided by standards issued by the Association of Road and Transport Professionals, *Verband der Strassen- und Verkehrsfachleute* (VSS). More specific design solutions are outlined in cantonal and municipal guidelines, such as the Cycling Standards, *Standards Veloverkehr* of Canton Zurich (Kanton Zürich, 2023) and the *Velostandards* of the City of Zurich (Stadt Zürich, 2024). Additionally, the *Federal Office of Roads* (ASTRA) has published a comprehensive collection of intersection design solutions, *Entflechtung der Veloführung in Kreuzungen* (ASTRA, 2022), which draws inspiration from Dutch best practices.

Beyond Switzerland, various cities and professional organizations have developed design guidelines for cycling and micromobility infrastructure. Among the most influential in recent years are the US-based *Urban Bikeway Design Guide* from the National Association of City Transportation Officials

(NACTO, 2025) and the Dutch *Design Manual for Bicycle Traffic* (CROW, 2016).

Several independent initiatives have also proposed design concepts for specific urban locations. Velokonferenz Schweiz and co.dex (2023) propose ambitious designs for typical streets and intersections in Switzerland. *Radbahn Berlin* (paper planes, 2017) envisions a high-comfort cycling route across the city, incorporating solutions for complex intersections, and *Perfecting the New York Street* (Davidson, 2021) presents a model for city-wide transformation using a representative street as a case study.

4.3 Design principles

Building on the E-Bike City concept outlined in Chapter 2, as well as various design guidelines and expert insights from the workshop, we have established a set of core design principles.

MAXIMUM SEPARATION Using lightweight modes in the E-Bike City will be as uninterrupted and conflict-free as possible. Where feasible, protected bike lanes, cycle tracks, and other dedicated facilities are implemented to ensure clear separation from motor vehicle traffic.

CONTINUITY AND CLARITY Users of all transportation modes will be able to navigate streets and intersections intuitively and with confidence. Colored cycling paths, continuous markings through intersections, and protected intersection designs enhance clarity and continuity.

GENEROUS CYCLING INFRASTRUCTURE Cycling facilities will provide adequate space for varying speeds, safe overtaking, and side-by-side riding. They will ensure sufficient capacity to support high volumes of bicycle traffic.

PRIORITIZING PUBLIC TRANSPORT High-quality public transportation must be preserved. The proposed designs will maintain all existing public transit routes and prioritize dedicated transit lanes, including exclusive bus lanes and center-running tram tracks, to prevent negative effects on travel times and punctuality.

AVOIDING DISADVANTAGES FOR PEDESTRIANS Walking is a fundamental pillar of urban mobility. Expanding cycling infrastructure will not come at the expense of pedestrian accessibility. The proposed street and intersection modifications will ensure that pedestrian facilities remain uninterrupted and that unintended conflicts between cyclists and pedestrians are minimized.

DISSOLVING CONFLICT POINTS Even at complex intersections, navigation will be safe and stress-free. Where possible, conflict points will be spatially separated to allow users to negotiate one conflict at a time.

MINIMIZING CONSTRUCTION WORK The E-Bike City transformation aims to achieve net-zero emissions by 2050. To support this transition, its implementation must be feasible within 10–20 years. Given that typical roadway infrastructure has a lifespan of approximately 50 years (BFS, 2024), the designs will prioritize solutions that minimize construction: Linear facilities, such as protected cycle tracks, are implemented within existing curbs using pavement markings and low-cost physical barriers. Intersection modifications will involve targeted curb adjustments with little or no impact on drainage or underground utilities.

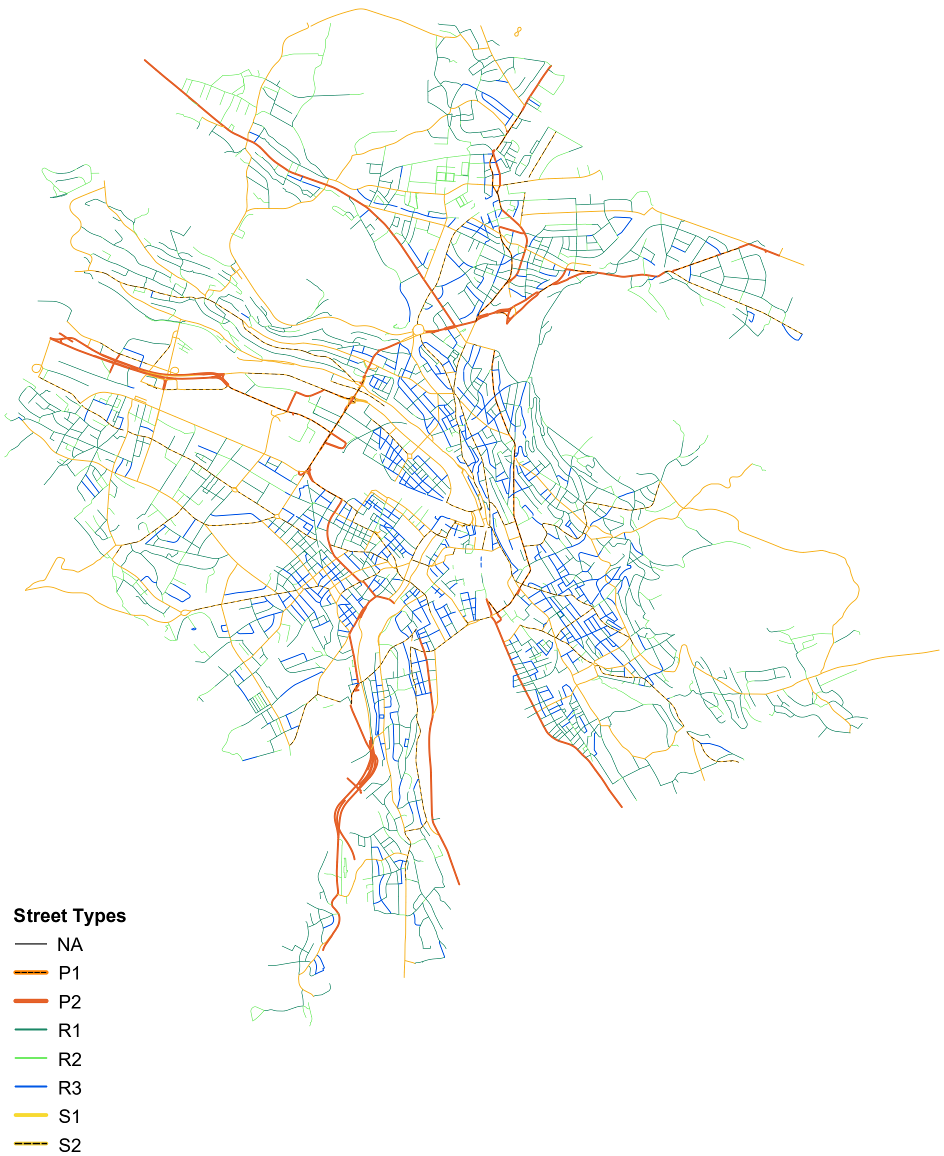
SUPPLY-DRIVEN PLANNING A central objective of the E-Bike City transformation is to influence mode choice by adjusting the relative convenience and efficiency of each transportation mode. Instead of allocating infrastructure based on predicted traffic volumes, we follow a proactive approach: infrastructure will be designed according to normative principles, and its impacts will be assessed afterward (see Chapter 5). Consequently, the allocation of travel lanes for motorized vehicles will be determined by functional street types (see Section 4.4) rather than the current traffic volumes.

4.4 Types of streets and intersections in Zurich

The street network in Zurich can be categorized into seven street types based on their functional hierarchy, traffic direction, presence of tram tracks, and on-street parking. The hierarchical classification follows OpenStreetMap (OSM) "highway" tagging, resulting in three primary levels: Residential (R), Secondary (S), and Primary (P). The secondary hierarchy level also includes streets tagged as "tertiary." For each street type, we calculate the median of its roadway widths, which later informs the possible design elements. Figure 4.1 provides an overview of all street types as of 2024.

The most prevalent street type, accounting for 37% of the total network length, consists of residential streets with one-way traffic and on-street parking and a width of 6.3 meters (in median). The second most common type are two-way secondary streets with on-street parking and no tram tracks (17.8%), and a width of 7.6 meters. Among secondary and primary streets, approximately one-quarter have tram tracks and a roadway width of approximately 12 meters.

Figure 4.1: Types of streets in Zurich



Type	Hierarchy Level	Dir.	Tram	Parking	Total length (km)	%	Median width (m)
R1	Residential Str.	↔	No	Yes	250	37.0	6.3
R2	Residential Str.	→	No	No	94	13.9	4.5
R3	Residential Str.	→	No	Yes	99	14.6	5.5
S1	Secondary Str.	↔	No	No	120	17.8	7.6
S2	Secondary Str.	↔	Yes	No	46	6.8	11.5
P1	Primary Str.	↔	Yes	No	12	1.8	12.0
P2	Primary Str.	↔	No	No	41	6.1	11.1
NA	(Other)				14	2.1	

A histogram of road widths, shown in Figure 4.2, shows that most streets in Zurich are less than 10 meters wide. Roadway widths of more than 15 meters occur only in rare cases.

Next, we classify intersections into five types based on the hierarchy levels of their adjoining streets. Additionally, a sixth category is introduced for intersections controlled by traffic signals. The majority of intersections are between residential streets (58%). The second most common type consists of intersections between residential and secondary streets (22%), followed by all signalized intersections (13%). All other intersection types are relatively rare, together accounting for only 7%. Figure 4.3 provides an overview.

Figure 4.2: Histogram of Road Widths in Zurich

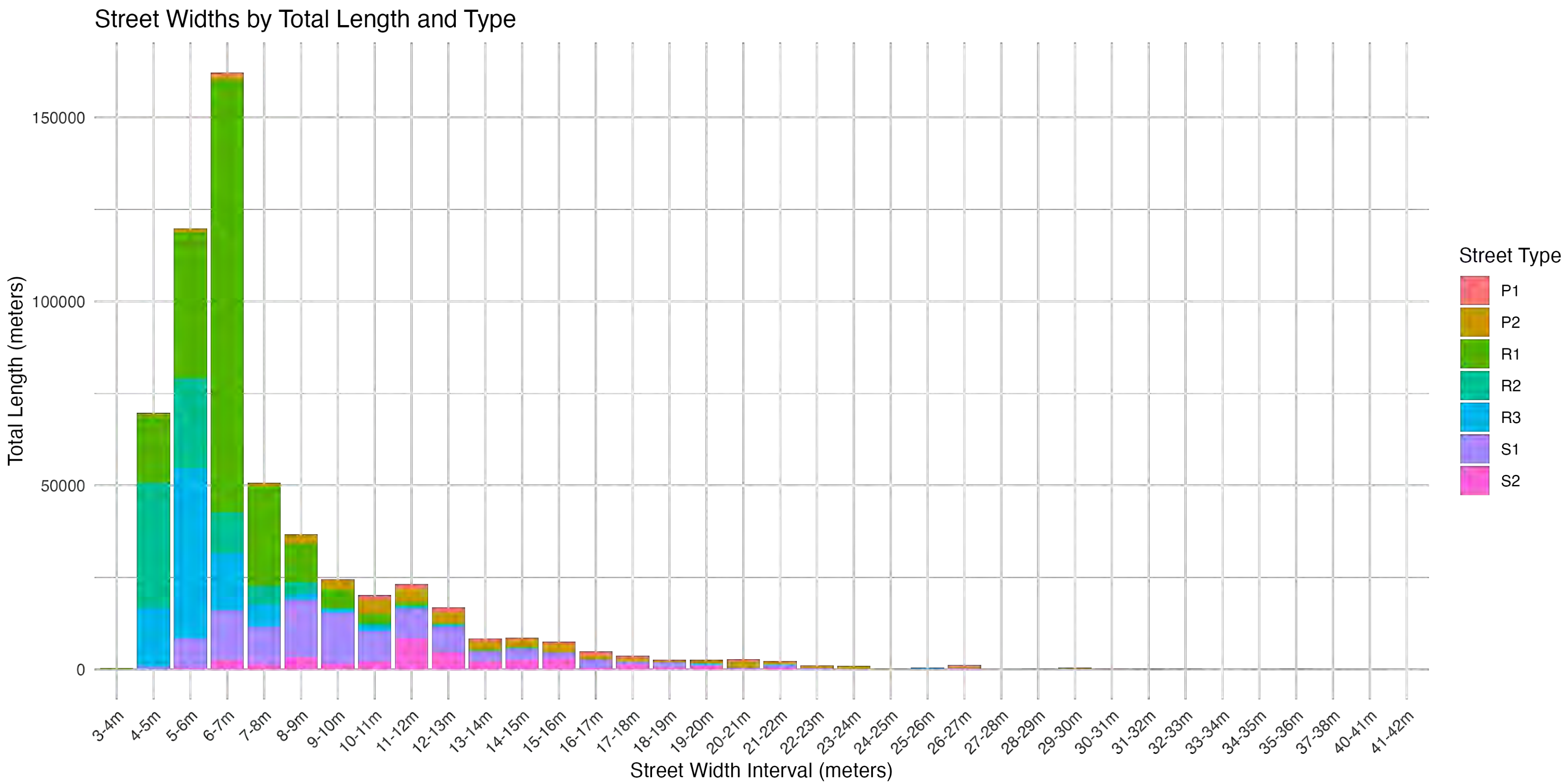
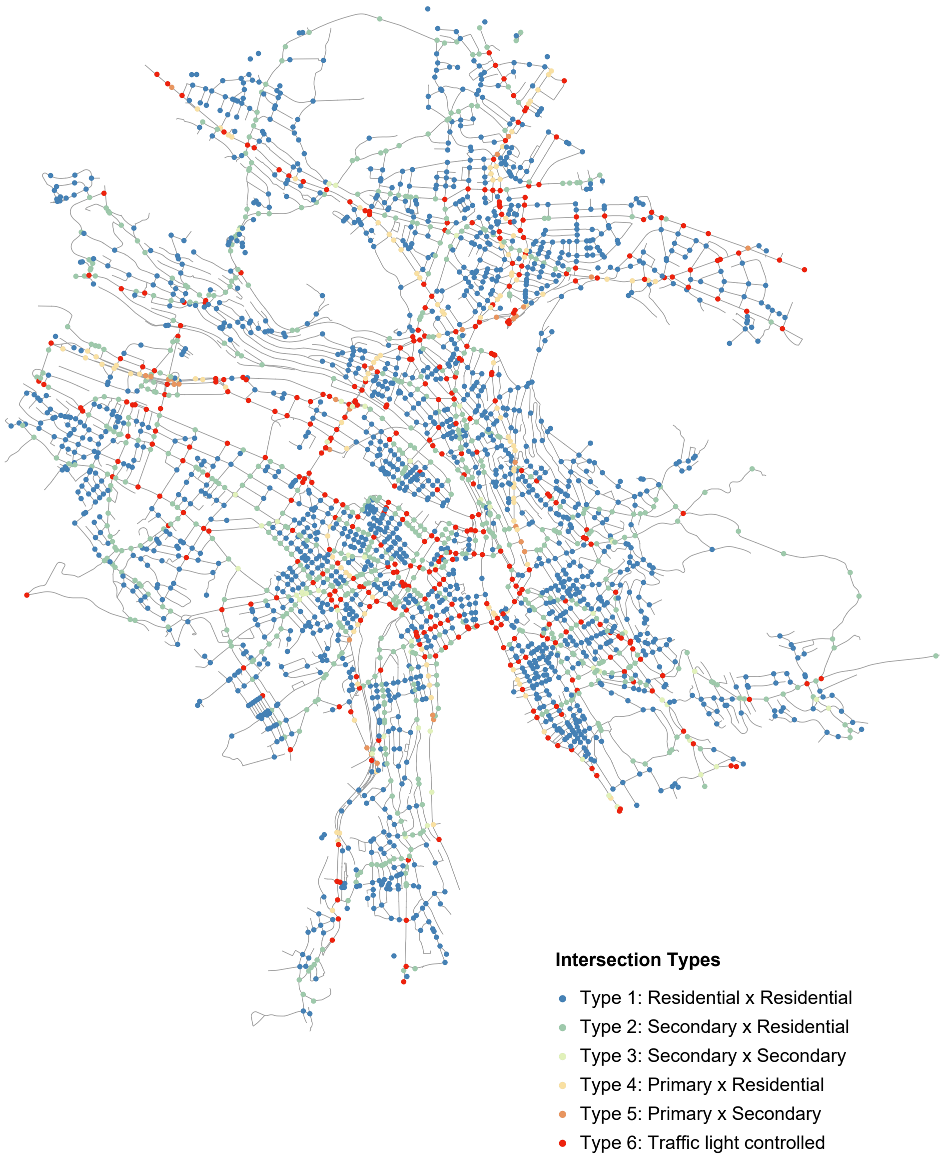


Figure 4.3: Types of intersections in Zurich



Type	Hierarchy Levels of Streets	Count	%
T1	Residential x Residential	1'809	58
T2	Secondary x Residential	693	22
T3	Secondary x Secondary	54	2
T4	Primary x Residential	118	4
T5	Primary x Secondary	31	1
T6	Signalized Intersection	392	13

4.5 Cycling infrastructure archetypes

We distinguish between three primary design archetypes for cycling infrastructure: one-way cycle lanes and separated cycle tracks, separated two-way cycle tracks, and cycling streets.

ONE-WAY CYCLE LANES AND SEPARATED CYCLE TRACKS The preferred solution consists of physically separated cycle tracks or lanes on both sides of the street, each accommodating cyclists traveling in a single direction. On residential streets with lower traffic volumes, a reduced version may involve a single contraflow cycle track or lane, allowing cyclists to travel in the opposite direction of motorized traffic.

SEPARATED TWO-WAY CYCLE TRACK In cases where existing immovable infrastructure prohibits one-way cycling facilities, a two-way cycle track may offer an alternative. However, such designs are suitable only for corridors with high bicycle through traffic rather than streets with frequent access points. Also, additional space at intersections is necessary to mitigate conflicts and ensure a continuous flow.

CYCLING STREET Residential streets with low volumes of motorized traffic may maintain mixed traffic. Reducing through traffic and adjusting the right of ways at intersections to prioritize important cycling flows allow a high cycling comfort despite no physical separation. Motorized traffic on these streets may be limited to emergency services, deliveries, and access to buildings. Future revisions of traffic law in Switzerland may additionally allow cyclists to ride side by side without allowing motor vehicles to overtake.

4.6 Design manual

We have applied the three archetypes of cycling infrastructure to each street type from Section 4.4 and created a manual of standard designs. It provides cross-section designs for combinations of street types and cycling infrastructure archetypes, as well as intersections between streets with different designs. It also provides an overview of the minimum and desired widths of the cycling infrastructure elements. See Appendix A for the complete design manual.

4.7 Design process

At the core of the design workshop was the creation of four specific designs for well-known locations in Zurich. This section outlines the design process in five steps.

DRAFTING THE EXISTING CONDITIONS We have used the CAD system Vectorworks 2024[1]. To model the current street environments, we imported two open datasets provided by the City of Zurich: 3D building data[2] and cadastral survey data[3]. Once the buildings and roadways were modeled, additional elements, such as road markings and tram shelters, were added manually based on aerial imagery.

IDENTIFYING FIXED INFRASTRUCTURE We distinguished between modifiable and fixed infrastructure elements within the street layout. To ensure the feasibility of near-term implementation, we minimized the modification of long-lasting infrastructure, such as tram tracks and curbs along linear facilities.

1 https://www.computerworks.ch/vectorworks
2 https://www.stadt-zuerich.ch/geodaten/download/Bauten___Kombinierte_Darstellung_mittelfristige_Zukunft
3 https://www.stadt-zuerich.ch/geodaten/download/10016

DEFINING FUNCTIONAL REQUIREMENTS To ensure functional consistency across the entire network, we defined the necessary travel directions and traffic access on each street based on the network plan described in Chapter 3, with local modifications if necessary.

SKETCHING DESIGN ALTERNATIVES Preliminary sketches were developed to explore various design solutions. Streets and intersections were configured using the design archetypes outlined in Section 4.5 and the standards from Appendix A. In most cases, a single archetype emerged as the most practical option. Where multiple solutions were feasible, we selected the one with the highest overall design coherence.

MODELING AND VISUALIZING THE SELECTED DESIGN The chosen design variant was modeled in the CAD environment. The visual style of the plans is inspired by Kanton Zürich (2023). The CAD data was then provided to the team at Nightnurse Images for creating photorealistic visualizations. For each location, we created four images: a bird' s-eye overview and the perspective of a cyclist, a driver, and a pedestrian.

4.8 Resulting designs for places in Zurich

This section presents the final designs for the four locations in Zurich. They were chosen to illustrate a diverse range of street typologies and design challenges, covering residential and secondary streets with and without public transport, as well as different types of intersections. Figure 4.4 and Table 4.1 provide an overview of the locations.

Figure 4.4: Design locations overview map

Table 4.1: Overview of design locations

Section	Location	Intersection Type	Related Design Standards	Description
4.8.1	Winterthurerstrasse x Letzistrasse	T6, (T2)	R1-A1 S2-A1 SR-A3	Secondary street with tram tracks and residential street
4.8.2	Herdernstrasse x Bullingerstrasse x Baslerstrasse	T2	S1-A1 S1-A2	Two secondary streets without tram tracks
4.8.3	Albisriederplatz	T6, (T2)	S2-A1 S2-A2	Two secondary streets with tram and/or bus routes
4.8.4	Langmauerstrasse x Scheuchzerstrasse	T4	R1-A1 RR-A1	Two residential streets

4.8.1 Winterthurerstrasse x Letzistrasse

SITUATION Winterthurerstrasse is a secondary street with center-running tram tracks and a single travel lane in each direction. It corresponds to street type S2 which covers a total length of 12 km across the city, much of which are unavoidable corridors for cyclists. The fixed tram tracks, combined with the principle of maintaining motorized traffic at least in one direction, substantially limit the set of feasible design solutions. The residential streets Röslistrasse and Letzistrasse require occasional motor vehicle access to residential areas around them and are too narrow (4.5 meters) to accommodate separated cycling infrastructure in both directions. In principle, two options are possible for Winterthurerstrasse: (1) Converting both travel lanes into spacious one-way cycling paths while sharing a single lane between trams and motorized traffic (design standard S2-A2), or (2) Converting only one travel lane into a two-way cycling path (S2-A1). Both solutions present challenges and conflict with some design principles outlined in Section 4.3.

DESIGN The tram tracks along Winterthurerstrasse will remain unchanged, with a full separation from other traffic and one travel lane will be converted into a bidirectional cycling path (S2-A1). Letzistrasse and Röslistrasse will follow a cycling street design (R1-A1). The resulting bidirectional cycling path has a width of 3.3-3.5 meters. Its width is close to the minimum for such facilities, which has potentially negative effects on capacity and comfort for cyclists, compared to more generous facilities. However, the alternative, introducing mixed traffic on the tram tracks would have negative effects on travel times of an important public transport connection. The resulting intersection is a crossing of a two-way cycling path and a cycling street with limited one-way motorized traffic. Traffic lights will regulate the tram crossing, as well as the passage of motorized vehicles through the cycling intersection. Partial adjustments of the curbs within the intersection will allow more space for navigating the complex conflicts in multiple steps.

SUMMARY The new design will provide a nearly full separation of cycling from motorized traffic. It will add a separated cycling path along the major secondary street Winterthurerstrasse and a cycling street on the residential streets Letzistrasse and Röslistrasse. The intersection for cyclists will be separated from car traffic, except for a limited number of vehicles accessing the nearby residential areas. Simultaneously, the proposed design will maintain the full separation of public transport, as well as motorized vehicle access on all streets.

Figure 4.5: Winterthurerstrasse x Letzistrasse, overview 1:1'500

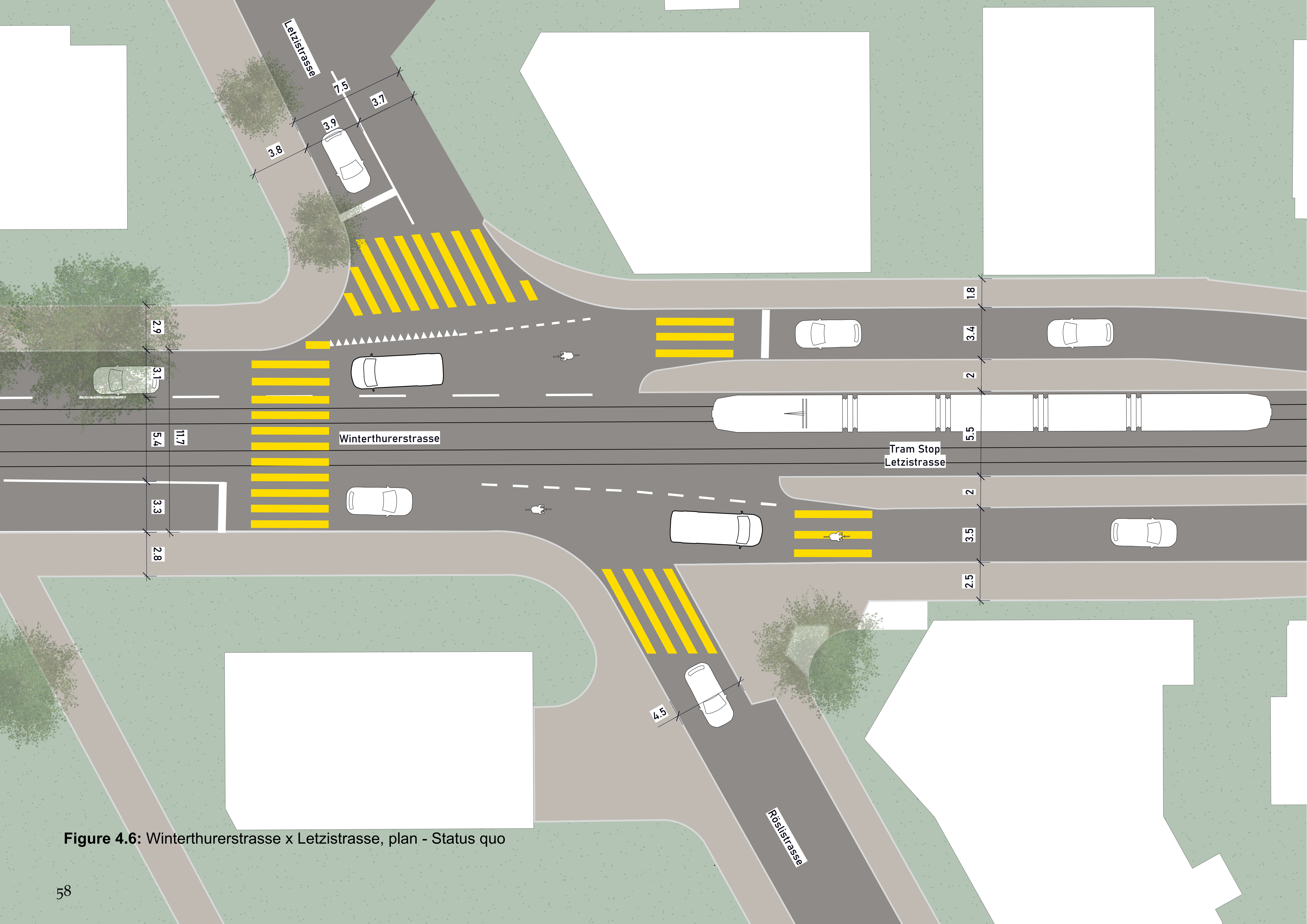


Figure 4.6: Winterthurerstrasse x Letzistrasse, plan - Status quo

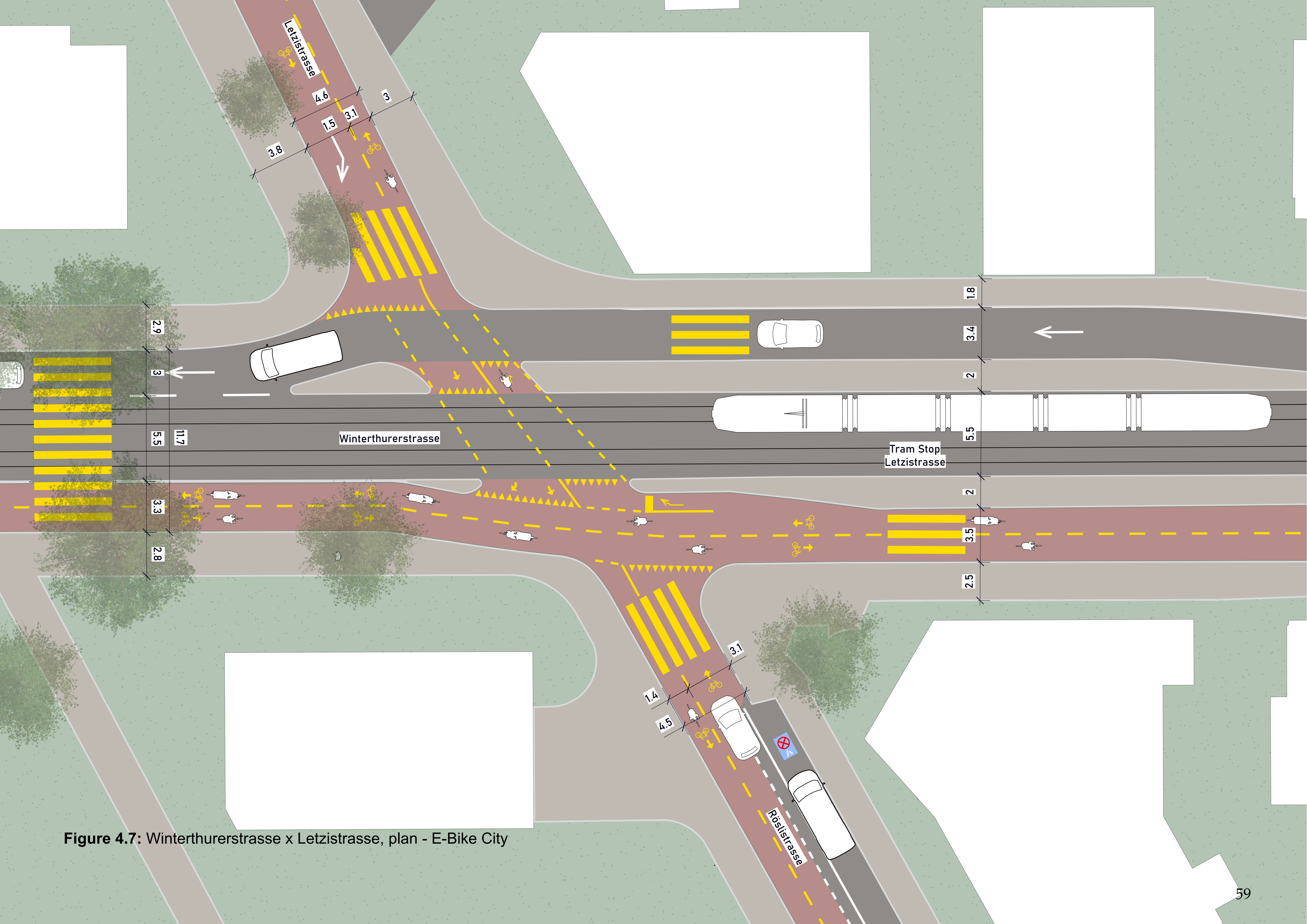


Figure 4.7: Winterthurerstrasse x Letzistrasse, plan - E-Bike City

Figure 4.8: Winterthurerstrasse x Letzistrasse, overview - Status quo

Figure 4.9: Winterthurerstrasse x Letzistrasse, overview - E-Bike City

Figure 4.10: Winterthurerstrasse x Letzistrasse, cyclist’s perspective - Status quo

Figure 4.11: Winterthurerstrasse x Letzistrasse, cyclist’s perspective - E-Bike City

Figure 4.12: Winterthurerstrasse x Letzistrasse, driver's perspective - Status quo

Figure 4.13: Winterthurerstrasse x Letzistrasse, driver's perspective - E-Bike City

Figure 4.14: Winterthurerstrasse x Letzistrasse, pedestrian's perspective - Status quo

Figure 4.15: Winterthurerstrasse x Letzistrasse, pedestrian's perspective - E-Bike City

4.8.2 Herdernstrasse x Bullingerstrasse x Baslerstrasse

SITUATION Herdernstrasse is a secondary street. Baslerstrasse and Bullingerstrasse are residential streets but their physical facilities are similar to secondary streets. These streets form part of a major cycling connection. To the south of the intersection is the bus depot Hardau. A route along Herndernstrasse and Bullingerstrasse is used by buses entering and exiting the facility.

DESIGN Herdernstrasse will be converted into a one-way street in the southbound direction, allowing buses to travel from the north to the depot. Buses exiting the depot will be redirected over Bullingerstrasse and Hardstrasse further east, and will then access the routes on Hohlstrasse through a tram stop on Hardplatz. Herdernstrasse will have a single lane for motorized traffic in the southbound direction and generous, one-way cycling paths with a width of 2 meters on both sides (S1-A1). Baslerstrasse and Bullingerstrasse will be transformed into a generous cycling street according to the design standard S1-A2 for secondary cycling streets. The intersection is designed with sufficient waiting areas, allowing users to navigate one conflict at a time. Optionally, traffic lights may be added to control the conflict between cyclists and buses.

SUMMARY The comfort of cycling will be massively improved by providing generous, physically separated cycling paths along Herdernstrasse and a wide cycling street along the corridor of Baslerstrasse and Buillingerstrasse. Large waiting areas and dissolved conflict points at the intersection will allow an intuitive and confident passage for all users. The access for motorized traffic will be maintained on all streets and the operation of buses entering and exiting the depot will still be possible.

Figure 4.16: Herdernstrasse x Baslerstrasse, overview 1:1'500

Figure 4.17: Herdernstrasse x Baslerstrasse, plan - Status quo

Figure 4.18: Herdernstrasse x Baslerstrasse, plan - E-Bike City

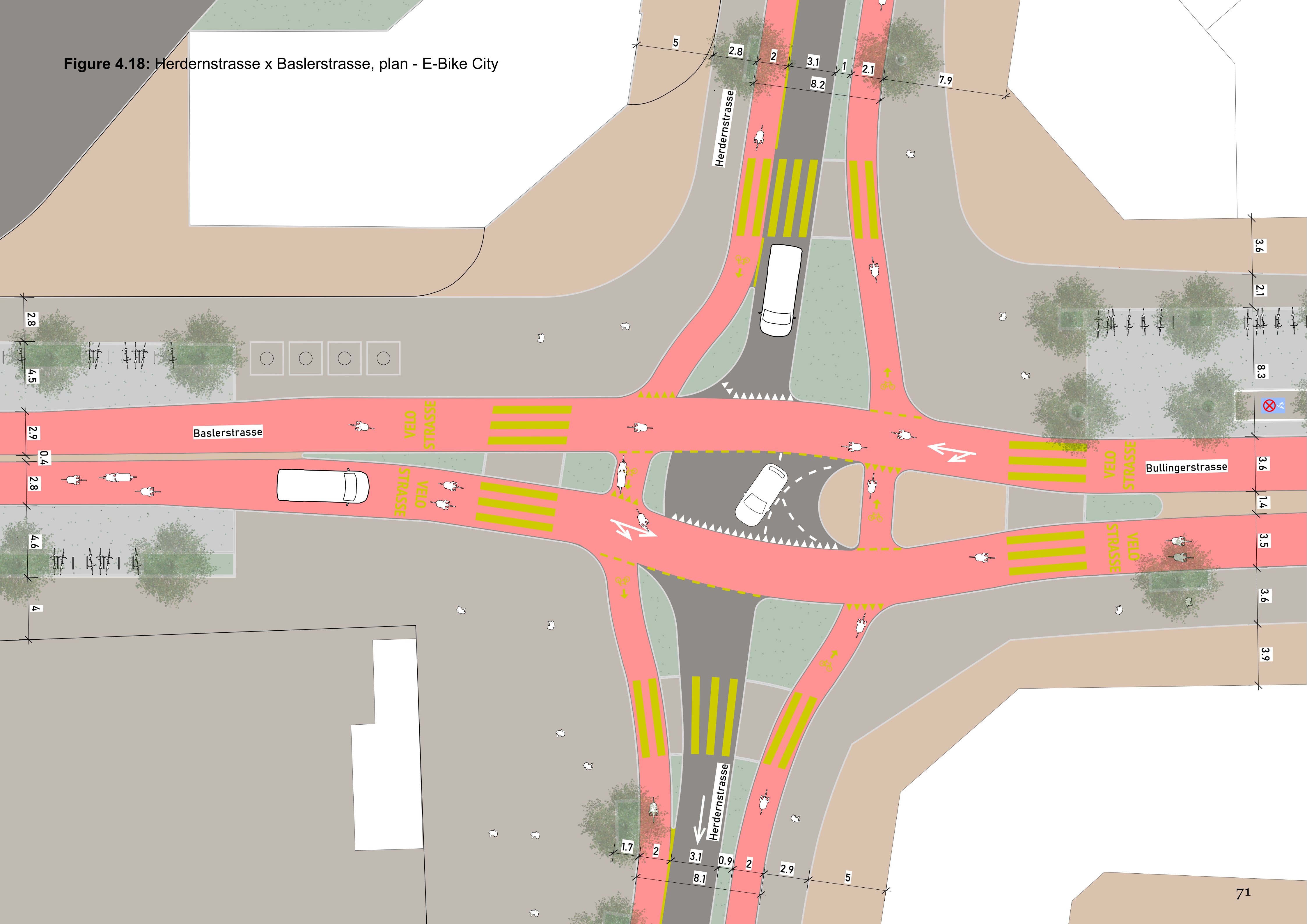


Figure 4.19: Herdernstrasse x Baslerstrasse, overview - Status quo

Figure 4.20: Herdernstrasse x Baslerstrasse, overview - E-Bike City

Figure 4.21: Herdernstrasse x Baslerstrasse, cyclist's perspective - Status quo

Figure 4.22: Herdernstrasse x Baslerstrasse, cyclist’s perspective - E-Bike City

Figure 4.23: Herdernstrasse x Baslerstrasse, driver's perspective - Status quo

Figure 4.24: Herdernstrasse x Baslerstrasse, driver’s perspective - E-Bike City

Figure 4.25: Herdernstrasse x Baslerstrasse, pedestrian's perspective - Status quo

Figure 4.26: Herdernstrasse x Baslerstrasse, pedestrian's perspective - E-Bike City

4.8.3 Albisriederplatz

SITUATION Albisriederplatz is a major intersection connecting the secondary streets Badenerstrasse, Albisriederstrasse, and Hardstrasse. Badenerstrasse and Albisriederstrasse have center-running tram tracks (street type S2). Hardstrasse is a secondary street without tram tracks (S1). Public transport operates on all four arms of the intersection in both directions. The intersection itself is structured as a roundabout, with a complex four-track tram station at its center. As in the case of Winterthurerstrasse (Section 4.8.1), the fixed tram tracks impose constraints on lane positioning. Additionally, bus routes on Hardstrasse prevent the implementation of a one-way traffic regime and existing bus stop infrastructure limits the set of designs that can be implemented without large construction.

DESIGN Badenerstrasse will be converted into a one-way street, with a bi-directional cycling path, following the design standard S2-A1. Due to its bus routes, Hardstrasse will retain two travel lanes, with the remaining space allocated for a one-way cycling path on each side. Its design follows a variation of S2-A1, without tram tracks. Albisriederstrasse will be designed based on a modified version of the same standard. However, in this case, motorized traffic will be restricted to buses and access to buildings. Buses will share the tram tracks and a limited-access motorized traffic will be accommodated under a cycling street regime. The bus stop on Albisriederstrasse will be shared with cyclists. The intersection design is optimized for minimum changes to the curbs (e.g., the cycling paths follow present curbs) and most changes can be at first implemented by using low-cost, mobile elements. Similarly, the infrastructure on the adjoining streets can be implemented with almost no construction.

SUMMARY The cycling infrastructure will be improved by providing separated cycling paths within the intersection and on most adjoining streets. Access for motorized traffic remains possible on all streets, as well as the operation of all present public transport routes. The construction needed for implementation will be minimized by avoiding changes to long-lasting infrastructure like tram tracks or curbs.

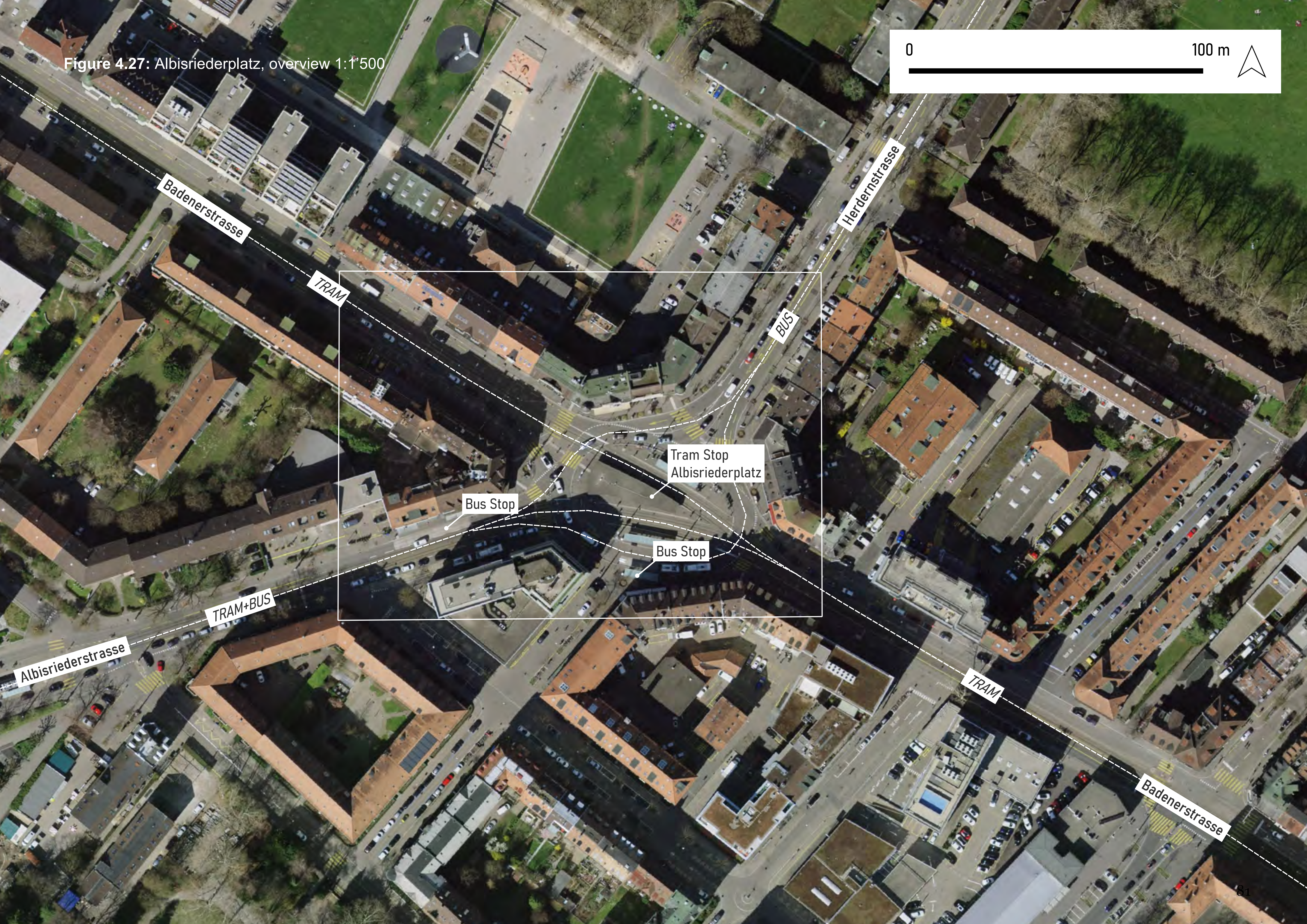


Figure 4.27: Albisriederplatz, overview 1:1'500

Figure 4.28: Albisriederplatz, plan - Status quo

Figure 4.29: Albisriederplatz, plan - E-Bike City

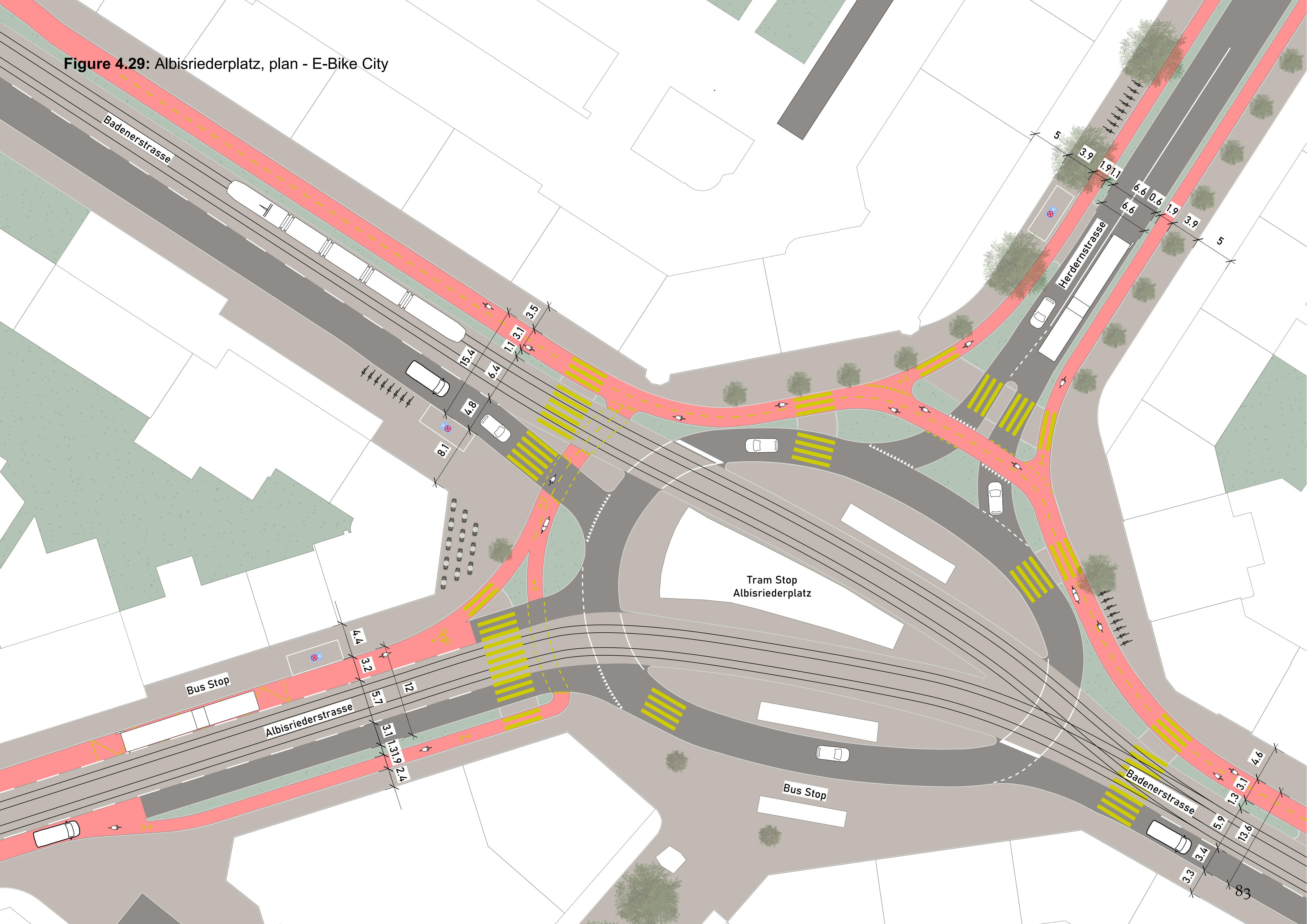


Figure 4.30: Albisriederplatz, overview - Status quo

Figure 4.31: Albisriederplatz, overview - E-Bike City

Figure 4.32: Albisriederplatz, cyclist's perspective - Status quo

Figure 4.33: Albisriederplatz, cyclist's perspective - E-Bike City

Figure 4.34: Albisriederplatz, driver’s perspective - Status quo

Figure 4.35: Albisriederplatz, driver's perspective - E-Bike City

Figure 4.36: Albisriederplatz, pedestrian's perspective - Status quo

Figure 4.37: Albisriederplatz, pedestrian's perspective - E-Bike City

4.8.4 Langmauerstrasse x Scheuchzerstrasse

SITUATION Langmauerstrasse and Scheuchzerstrasse are residential streets with on-street parking. Langmauerstrasse accommodates two-way traffic (type R1), while Scheuchzerstrasse is a one-way street (type R3). Neither street is part of a public transport route.

DESIGN Three arms of the intersection will be converted into bidirectional cycling streets with a one-way traffic regime for motorized vehicles (design standard R1-A1). A limited number of on-street parking spaces will be retained to accommodate access for people with disabilities and utility vehicles. The northern section of Langmauerstrasse will be converted into a dedicated cycling path, with car traffic restricted to vehicles accessing the adjacent buildings. The intersection itself will be designed as a shared traffic space, giving priority to crossing pedestrians.

SUMMARY The attractiveness of cycling on the residential streets will be improved by converting them into cycling streets or cycling paths. The intersection itself will favor pedestrians by providing a mixed traffic space where they have priority over cyclists and drivers.

Figure 4.38: Langmauerstrasse overview 1:1'500

Figure 4.39: Langmauerstrasse, plan - Status quo

Figure 4.40: Langmauerstrasse, plan - E-Bike City

Figure 4.41: Langmauerstrasse, overview - Status quo

Figure 4.42: Langmauerstrasse, overview - E-Bike City

Figure 4.43: Langmauerstrasse, cyclist's perspective - Status quo

Figure 4.44: Langmauerstrasse, cyclist's perspective - E-Bike City

Figure 4.45: Langmauerstrasse, driver's perspective - Status quo

Figure 4.46: Langmauerstrasse, driver's perspective - E-Bike City

Figure 4.47: Langmauerstrasse, pedestrian's perspective - Status quo

Figure 4.48: Langmauerstrasse, pedestrian’s perspective - E-Bike City

Chapter 5: Accessibility Effects

This chapter is a revised and updated version of the following peer-previewed conference contribution:

Ballo, L., A. Sallard, L. Meyer de Freitas and K. W. Axhausen (2025) Is "small" infrastructure the next factory for accessibility? Evaluating the regional accessibility effects of a cycling-centric transport policy in Zurich, presented at the *104th Annual Meeting of the Transportation Research Board* (*TRB 2025*), Washington DC, January 5-9.

The individual contributions of Lukas Ballo are conceptualization, carrying out the accessibility and equity analysis, and manuscript writing. Lucas Meyer de Freitas contributed the mode choice model and part of the data on mobility in Zurich in Section 5.2. Aurore Sallard carried out the MATSim simulation and calibrated the mode choice model. Kay W. Axhausen provided helpful inputs in the conceptualization and revising stages.

5.1 Introduction

Decades of transport infrastructure investments in Switzerland have created substantial accessibility improvements (Axhausen *et al.*, 2011). Increasing speeds and decreasing travel costs have delivered economic benefits in consumer choice, specialization, and residential options. Easier and cheaper travel has allowed individuals to reach more destinations and develop lower-density settlements with more residential space. However, this mechanism is increasingly being questioned. Further extensive infrastructure such as highways or heavy rail in today's complex environments can only be built at a rapidly increasing cost, with a high proportion of bridges and tunnels (Wampfler and Ottinger, 2013). Moreover, the resulting increase in travel distances and traffic volumes starkly conflicts with the urgent need to decarbonize the transport sector (Axhausen, 2022; IPCC, 2022).

Contemporary ideas like the 15-Minute city (Moreno *et al.*, 2021) or urban Superblocks (Rueda, 2019) suggest a different approach, emphasizing the benefits of sustainable mobility choices and proximity rather than high maximum speeds. In these proposals, relatively small and modular changes shift the mode choice toward public transport and lightweight vehicles. In the context of this work, we term these two approaches the "large infrastructure" and "small infrastructure" paradigms. This chapter explores the accessibility effects of the E-Bike City in Zurich as an example of the latter paradigm. It changes mode choice and accessibility by re-purposing existing facilities in favor of flexible lightweight modes rather than building new ones for high maximum speeds.

We use the hypothetical transport network introduced in Chapter 3 and analyze its effects on traffic, mode choice, accessibility, and equity for different population groups. We use an agent-based simulation in MATsim/Equasim (Horni *et al.*, 2016; Hörl and Balac, 2021), together with a logsum accessibility measure (Ben-Akiva and Lerman, 1979). Finally, we report the effects on traffic volumes and the accessibility changes felt by each population group. The MATsim simulations, as well as the accessibility calculations, were carried out on the Euler computing cluster of ETH Zurich. The rest of this chapter is structured as follows: Section 5.2 describes today's mobility patterns in Zurich based on the official travel survey, Section 5.3 shows previous contributions, Section 5.4 describes the methods, Section 5.5 provides the results. Sections 5.7 and 6 add a discussion of the results and conclude this chapter.

5.2 Mobility in Zurich

As of 2024, the City of Zurich had a total population of 443'037 inhabitants, an area of 91.9 km^2, and roughly 1.9 million individuals living within its larger metropolitan region (City of Zurich, 2024c). Table 5.1 provides an overview of today's travel patterns in Zurich based on trips reported in the Swiss national travel survey conducted in 2021 (BFS and ARE, 2023). For footnotes, refer to the page after the table.

Trips within the municipal borders are done mainly using public transport, walking, and cycling. Only 28.4% of person-kilometers (pkm) are traveled by car. The remaining distance traveled relies on public transport (31.3%), walking (23%), and cycling (15%). For cross-border trips (only considering their part within the city), cars account for a mode share of 40.4%. However, despite these moderate shares, they are responsible for 60.6% of vehicle kilometers (vkm), including bicycles, and 83.8% of all traffic-related CO_2 emissions within the city borders. Even if the cross-border trips, accounting for 45.5% of vkm within the city are excluded, the local car trips account for almost 50% of Zurich's transport CO_2 emissions.

Replacing the entire car fleet with battery-electric vehicles would theoretically reduce the emissions of car traffic by roughly 50% compared to the fleet in 2024, to 89.8 g CO_2/pkm, cutting Zurich's transport emissions by about 40%. But even in that case, car traffic will still account for 74.2% of transport emissions. Lower costs in operating electric vehicles and the potential adoption of autonomous driving may induce more car traffic and eliminate some of these benefits. Thus, redesigning the transport system in favor of other modes has a large potential for reducing emissions while potentially generating adverse effects only for a moderate proportion of trips.

Table 5.1: Mobility indicators for Zurich based on the Swiss national travel survey (BFS and ARE, 2023)

		Motorcycle	E-Bike	Cars	Public transport	Bicycle	Walking	All modes	All excl. walking
average occupancy		1.0	1.0	1.5	20.0[4]	1.0	-	-	-
emissions CO2 eq[1]	g/km	163.6	11.3	186.4[2]	25.4	5.6	0.0	-	-
sample scaling[3]		164	164	164	164	164	164	-	-
Trips within the city									
person km traveled (sample)	km	202	793	13’030	14’360	6’886	10’549	45’820	35’271
person km traveled	km	33’044	129’721	2’131’484	2’349’049	1’126’431	1’725’635	7’495’365	5’769’730
vehicle km traveled	km	33’044	129’721	1’420’989	117’452	1’126’431	0	2’827’638	2’827’638
person km share	%	0.4%	1.7%	28.4%	31.3%	15.0%	23.0%	100.0%	77.0%
vehicle km share	%	1.2%	4.6%	50.3%	4.2%	39.8%	0.0%	100.0%	100.0%
emissions CO2 eq.	t	5.4	1.5	397.3	59.7	6.3	0.0	470.2	470.2
share of emissions	%	1.1%	0.3%	84.5%	12.7%	1.3%	0.0%	100.0%	100.0%
Trips across city borders									
person km traveled (sample)	km	1’189	416	113’723	137’841	2’488	631	256’288	255’657
person km traveled	km	194’527	67’975	18’603’186	22’548’356	406’980	103’273	41’924’296	41’821’023
vehicle km traveled	km	194’527	67’975	12’402’124	1’127’418	406’980	0	14’199’023	14’199’023
person km share	%	0.5%	0.2%	44.4%	53.8%	1.0%	0.2%	100.0%	99.8%
vehicle km share	%	1.4%	0.5%	87.3%	7.9%	2.9%	0.0%	100.0%	100.0%
emissions CO2 eq.	t	31.8	0.8	3’467.6	572.7	2.3	0.0	4’075.2	4’075.2
share of emissions	%	0.8%	0.0%	85.1%	14.1%	0.1%	0.0%	100.0%	100.0%
Trips across city borders (part within the city)									
person km traveled (sample)	km	238	83	10’865	14’658	712	316	26’872	26’556
person km traveled	km	38’933	13’577	1’777’327	2’397’797	116’471	51’692	4’395’798	4’344’106
vehicle km traveled	km	38’933	13’577	1’184’885	119’890	116’471	0	1’473’756	1’473’756
person km share	%	0.9%	0.3%	40.4%	54.5%	2.6%	1.2%	100.0%	98.8%
vehicle km share	%	2.6%	0.9%	80.4%	8.1%	7.9%	0.0%	100.0%	100.0%
emissions CO2 eq.	t	6.4	0.2	331.3	60.9	0.7	0.0	399.4	399.4
share of emissions	%	1.6%	0.0%	83.0%	15.2%	0.2%	0.0%	100.0%	100.0%
All traffic within the city									
person km traveled (sample)	km	440	876	23’895	29’018	7’598	10’865	72’692	61’827
person km traveled	km	71’976	143’299	3’908’812	4’746’846	1’242’902	1’777’327	11’891’163	10’113’835
vehicle km traveled	km	71’976	143’299	2’605’874	237’342	1’242’902	0	4’301’394	4’301’394
person km share	%	0.6%	1.2%	32.9%	39.9%	10.5%	14.9%	100.0%	85.1%
vehicle km share	%	1.7%	3.3%	60.6%	5.5%	28.9%	0.0%	100.0%	100.0%
share of cross-border trips in person km	%	54.1%	9.5%	45.5%	50.5%	9.4%	2.9%	37.0%	43.0%
share of cross-border trips in vehicle-km	%	54.1%	9.5%	45.5%	50.5%	9.4%	-	34.3%	34.3%
emissions CO2 eq.	t	11.8	1.6	728.6	120.6	7.0	0.0	869.5	869.5
share of emissions	%	1.4%	0.2%	83.8%	13.9%	0.8%	0.0%	100.0%	100.0%

5.3 Previous work

5.3.1 Accessibility measures

Many definitions of accessibility can represent the performance of transport and land-use systems. Geurs and van Wee (2004) and Miller (2018) propose systematic overviews of different accessibility types. We distinguish three main types of accessibility measures: cumulative, gravity-based, and utility-based.

CUMULATIVE MEASURES These measures show a total number of destinations within a given travel time (e.g., number of jobs within 30 minutes). They have relatively low computational complexity and are easy to interpret. On the other hand, they require normative judgment about a hard cut-off limit and have limitations in capturing the total effects of measures involving different modes.

GRAVITY-BASED MEASURES Unlike cumulative measures, gravity measures (e.g., Hansen (1959)) remove the need to set a fixed boundary. They consider all destinations within a larger area while discounting their value with a decay function related to travel time or the generalized cost of reaching them. However, similarly to the cumulative measures, they are typically shown for each mode separately. While it is possible to add a mode choice model to account for different modes, such a formulation is inconsistent with random utility theory, leading to possibly incorrect conclusions about utility resulting from policies that redistribute priority between modes, such as the E-Bike City.

LOGSUM MEASURES Similar to the above, Logsum measures consider all possibly reachable destinations. However, instead of using decay functions and accessibility contributions, they rely on a definition consistent with random-utility theory, creating a framework compatible with utility functions in discrete mode and destination choice models. As a result, they can represent the impacts on each individual's utility after adjusting to the new choice situations. The underlying theory was proposed in Ben-Akiva and Lerman (1979). Considering weights for destinations and personal characteristics of individuals making trips, the model is also consistent with the capability approach (Sen, 2009): It captures the combination of place-based opportunities and personal capabilities while explicitly accounting for the value of unchosen, yet available options.

5.3.2 Applications of logsum accessibility measures

Multiple studies have applied logsum accessibility to evaluate complex changes in the built environments and their effects on equity. Geurs *et al.* (2010) study the effects of simultaneous changes to infrastructure and land use in the Netherlands. Guzman *et al.* (2023) monetize the effects of additional train and metro routes in Bogotá. Dixit and Sivakumar (2020) apply different variations of the logsum measure to study the accessibility and equity effects in the Greater London area. They show how including personal characteristics in the accessibility measure helps capture important equity effects. Bills *et al.* (2022) analyze the effects of new microtransit services in Detroit, Michigan, and use a logsum measure to explore the equity effects among different income groups.

1 Mobitool Swiss emission factors per passenger km: `https://www.mobitool.ch/de/tools/mobitool-faktoren-v3-0-25.html?tag=18`, Fleet averages in 2024, including all propulsion types
2 Average value for today's fleet, for battery electric vehicles: 89.8 g CO2 eq./pkm
3 Swiss Population 9'000'000 / Sample size 55'018
4 Assumption: 20 persons per public transport vehicle

5.3.3 Representing cycling comfort in models

Unlike the "large infrastructure" paradigm, where the benefits can be expressed by considering travel time savings, studying "small infrastructure" requires a different approach. Policies like the E-Bike City do not change cycling travel times substantially but rather make the usage of bicycles more attractive through dedicated road space. We need to use an econometric model to capture the benefits and mode choice effects of these changes. Meister *et al.* (2023) estimated a route choice model for Zurich from data obtained in a GPS Tracking study (Molloy *et al.*, 2021). Its parameters were converted into Value of Distance (VoD) Indicators that enable a conversion between cycling infrastructure characteristics and distance. Thus, the infrastructure changes can be represented as distortions in link lengths. See Chapter 3 for further background and literature on this topic.

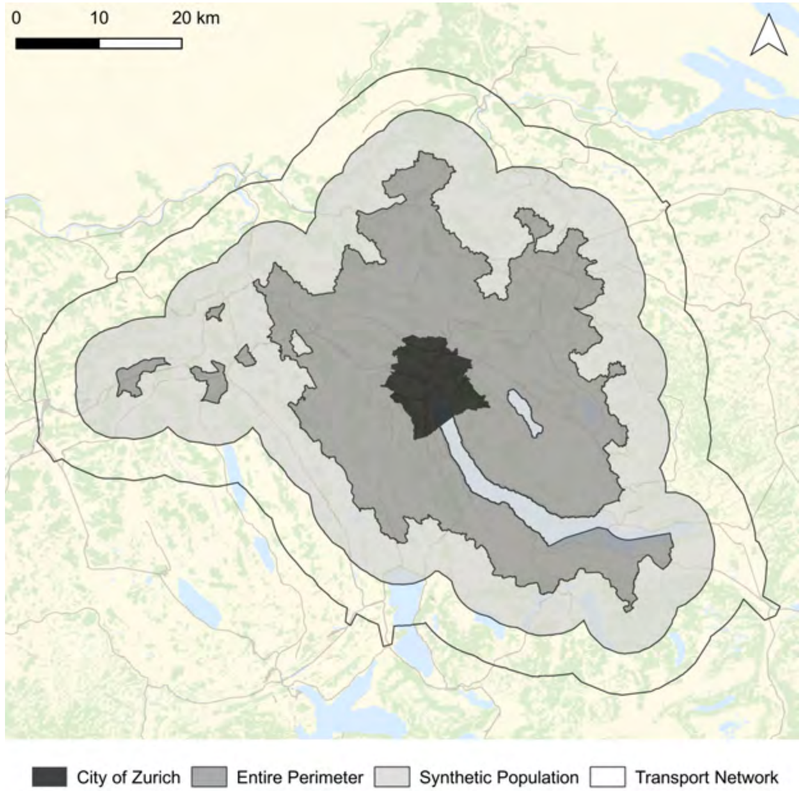
5.4 Methods

5.4.1 Perimeter

The perimeter for analyzing the accessibility effects covers the larger Zurich area (1'343 km^2). We define it as all municipalities with at least 15% of their population commuting to the City of Zurich according to the Swiss commuting statistics[1]. For generating travel demand in the MATSim model, the synthetic population is provided for the same area plus a 5 km buffer. Trips beyond that buffer are represented by their portions cut out of the nationwide model (Tchervenkov *et al.*, 2022). The transportation network includes an additional buffer of 5 km, with local extensions for adjacent highway interchanges to avoid long disconnected road sections. Figure 5.1 shows a map of the perimeter geometries.

1 https://www.bfs.admin.ch/bfs/en/home/statistics/mobility-transport/passenger-transport/commuting.html

Figure 5.1: Perimeter geometries



5.4.2 Dataset on population and destinations

The population data is provided by the 2017 STATPOP dataset of Switzerland[2]. It represents the home location of each perma-

2 https://www.bfs.admin.ch/bfs/de/home/statistiken/kataloge-datenbanken.assetdetail.27965868.html

nent resident, with attributes such as age, sex, and residence permit, but no data on income and mobility tool ownership. The residential locations in this dataset show slight spatial disparities, with a higher-than-average proportion of foreigners, younger residents, and males at central locations. The destinations used in the accessibility calculation are based on the aggregated STATENT dataset[3], containing economic information, such as the number of firms and jobs, aggregated to cells of 100x100 meters.

5.4.3 Transportation network

The transportation networks representing the status quo and the transformation to an E-Bike City are generated with the `snman` Python software package, introduced in Chapter 3. The status quo network is based on OpenStreetMap (OSM) data, enriched with local, official datasets on public transport routes and on-street parking. The rebuilt network allocates a large proportion of the existing road space within the city to separated cycling paths and reorganizes the remaining travel lanes to provide access for essential car trips. It creates an extensive infrastructure for cycling and other micromobility vehicles while keeping the total road width on every street unchanged. The transformation is limited to an area that roughly corresponds to the municipal boundary. No changes are made beyond this area.

Through the transformation, the proportion of road space allocated to cycling infrastructure increased from 12.1% to 54.3%, while the space for motorized traffic lanes decreased from 66.6% to 35.1%. As a result of many one-way streets and detours in the reorganized network for car traffic, the average shortest path for car trips increases by 35.7%. On the other hand, the higher proportion of streets with cycling infrastructure reduces the generalized cost for cycling trips at a level equivalent to reducing their average shortest path by 24.1% (the VoD indicators translate cycling infrastructure benefits into distance reduction). See Table 3.4 in Chapter 3 for descriptive statistics of the current and rebuilt transportation network.

Table 5.2: Value of Distance indicators for grades

Grade	Bicycle	E-Bike (Pedelec/S-Pedelec)
slope < 2%	0	0
2% ≤slope < 6%	+0.55	+0.09
6% ≤slope < 10%	+3.11	+1.01
10% ≤slope	+4.33	+2.78

The effects of dedicated infrastructure and grades on cyclists are considered by pre-calculating link lengths after distortion by the VoD indicators from Meister *et al.* (2023). See Chapter 3 for details on calculating the link lengths. In this chapter, we additionally consider the benefits of E-Bikes by differentiating the VoD indicators for grades, also based on the work in Meister *et al.* (2023). See Table 5.2 for an overview of the values used.

We also considered including the effects of car traffic volumes on cyclists. However, the results in Meister *et al.* (2023) don't allow a consistent implementation of such an extension in our model. Since the authors didn't succeed in estimating robust link-based VoD indicators for traffic volumes, they only report indicators for maximum traffic volumes along each route. However, these cannot be directly translated to our link-based approach. Moreover, the difference between the reported values for high (>10k) and low (1-10k) traffic volumes has only a small impact on the total trip cost, compared to the benefits of

3 https://www.bfs.admin.ch/bfs/de/home/dienstleistungen/geostat/geodaten-bundesstatistik/arbeitsstaetten-beschaeftigung/statistik-unternehmensstruktur-statent-ab-2011.html

cycling infrastructure. Thus, in this work, we omit the effects of car traffic volumes on cyclists.

5.4.4 MATSim simulation

We use an agent-based simulation to obtain car travel times on the congested network, total traffic volumes for all modes, and mode shares. In post-processing, the resulting car travel time on each link is aggregated into 30-minute bins. In the subsequent accessibility calculation, travel time losses due to congestion are only considered for cars. For other modes, any link travel times from MATSim are ignored.

The simulation setup is derived from the Switzerland scenario introduced by Tchervenkov *et al.* (2022). We use MATSim 15 (Horni *et al.*, 2016) together with the Equasim pipeline (Hörl and Balac, 2021), which replaces MATSim's utility functions with discrete choice models. Sonnak (2024) describes the initial process of cutting the desired perimeter out of the national scenario, with a resulting synthetic population of roughly 2.6 million agents, and adjusting it to the specifics of the E-Bike City idea. The scenarios before and after rebuilding differ only in the underlying network and are based on today's land use, population, travel behavior, and mobility tool ownership. Also, no changes were made to the organization of logistics, delivery services, and other freight traffic.

Eight transport modes are modeled (in MATSim terminology): "bike", "ebike", "spedelec", "car", "car passenger", "truck", "walk", and "public transport". Only tours containing car, bike, ebike, spedelec, public transport, and walking trips can change modes during the replanning stage. We don't permit changes in destination choice, and trips crossing the synthetic population perimeter are constrained to their original mode and crossing point. All motorized and cycling-related individual modes are routed on the network, which allows us to model the effects of congestion. For cycling, we use a "seepage" link dynamics (Agarwal and Lämmel, 2016) on links shared with motorized traffic – they are affected by congestion but can seep through the queues. These effects of congestion on cyclists, however, only apply in the simulation, indirectly (through mode choice) affecting the car traffic volumes and travel times, but they are not used in the later accessibility calculation. Walking and public transport are modeled as teleported modes. Any effects of additional congestion on the punctuality of public transport are neglected, which is reasonable to some extent, given that all dedicated bus lanes and the effective priority at signalized intersections remain unchanged. Any systematic congestion-related delays in public transport occurring in the status quo are already included in the official scheduled travel times, which are generally longer for the peak hours than for the rest of the day. Further details of the process and the exact datasets used are described in Appendix C.

5.4.5 Mode choice model

The mode choice model used in the MATSim simulation, as well as for the subsequent logsum accessibility measure, is based on a newer version of the work presented in Meyer de Freitas and Axhausen (2024). The model was estimated with data from the E-Biking in Switzerland (EBIS) dataset (Heinonen *et al.*, 2024) and was developed to consider not only conventional bicycles but also e-bikes. It includes cars, public transport, cycling, pedelecs (conventional E-Bikes with electric support up to 25 km/h and max. 500 Watt), s-pedelecs (fast E-Bikes up to 45 km/h and 1 kW, requiring a driving license), and walking. It considers characteristics of trips (distance, travel time, purpose), person (age and sex), and destination (within or outside the City of Zurich). The data collection and estimation were done with the following assumptions about mode availability: Cars are available to individuals with driver's licenses. Cycling modes are considered only for trips of up to 40 Kilometers. The model is defined as a multinomial logit, which makes it compatible with the discrete choice implementation in Equasim. After an initial estimation, it was further calibrated for the MATSim scenario. Some model parameters were adjusted such that the resulting mode choice matches the Swiss travel survey (BFS and ARE, 2023). See Appendix C for detailed documentation of the process and the changes made to some parameters. Below is the formulation of the utility functions. Generally, age is in years, distance in kilometers, and duration in hours. The model parameters are shown in Table 5.3. Some attributes in the utility functions are not directly available in the population dataset or shortest path calculations used in this work. Table 5.4 shows how these attributes were calculated or replaced by reasonable assumptions.

Car utility

$$\begin{aligned} U_{\text{car}} &= \alpha_{\text{car}} \\ &+ \beta_{\text{TT,car}} x_{\text{TT,car}} \\ &+ \beta_{\text{parking cost}} x_{\text{parking cost}} \\ &+ \beta_{\text{cost}} x_{\text{cost,car}} \\ &+ \beta_{\text{externalities,car}} \gamma_{\text{externalities by km,car}} x_{\text{in-veh dist,car}} \end{aligned} \tag{5.1}$$

Public transport utility

$$\begin{aligned} U_{\text{PT}} &= \alpha_{\text{PT}} \\ &+ \beta_{\text{female,PT}} x_{\text{sex==female}} \\ &+ \beta_{\text{age,PT}} x_{\text{age}} \\ &+ \beta_{\text{degurba2,PT}} x_{\text{degurba==medium}} \\ &+ \beta_{\text{degurba3,PT}} x_{\text{degurba==low}} \\ &+ \beta_{\text{TT,PT}} x_{\text{TT,PT}} \\ &+ \beta_{\text{access egress time,PT}} x_{\text{access egress time,PT}} \\ &+ \beta_{\text{freq}} x_{\text{freq,PT}} \\ &+ \beta_{\text{cost}} x_{\text{cost,PT}} \\ &+ \beta_{\text{externalities,PT}} \gamma_{\text{externalities by km,PT}} x_{\text{in-vehicle distance,PT}} \end{aligned} \tag{5.2}$$

Bicycle utility

$$\begin{aligned} U_{\text{bike}} &= \alpha_{\text{bike}} \\ &+ \beta_{\text{female,bike}} x_{\text{sex==female}} \\ &+ \beta_{\text{age,bike}} x_{\text{age}} \\ &+ \beta_{\text{degurba2,bike}} x_{\text{degurba==medium}} \\ &+ \beta_{\text{degurba3,bike}} x_{\text{degurba==low}} \\ &+ \beta_{\text{TT,bike}} x_{\text{TT,bike}} \\ &+ \beta_{\text{cost}} x_{\text{cost,bike}} \\ &+ \beta_{\text{externalities,bike}} \gamma_{\text{externalities by km,bike}} x_{\text{distance,bike}} \end{aligned} \tag{5.3}$$

E-Bike (Pedelec) utility

$$\begin{aligned}U_{\text{ebike}} &= \alpha_{\text{ebike}}\\&+ \beta_{\text{female,ebike}} x_{\text{sex==female}}\\&+ \beta_{\text{age,ebike}} x_{\text{age}}\\&+ \beta_{\text{degurba2,ebike}} x_{\text{degurba==medium}}\\&+ \beta_{\text{degurba3,ebike}} x_{\text{degurba==low}}\\&+ \beta_{\text{TT,ebike}} x_{\text{TT,ebike}}\\&+ \beta_{\text{cost}} x_{\text{cost,ebike}}\\&+ \beta_{\text{externalities,ebike}} \gamma_{\text{externalities by km,ebike}} x_{\text{distance,ebike}}\end{aligned} \tag{5.4}$$

E-Bike (S-Pedelec) utility

$$\begin{aligned}U_{\text{Spedelec}} &= \alpha_{\text{Spedelec}}\\&+ \beta_{\text{female,Spedelec}} x_{\text{sex==female}}\\&+ \beta_{\text{age,Spedelec}} x_{\text{age}}\\&+ \beta_{\text{degurba2,Spedelec}} x_{\text{degurba==medium}}\\&+ \beta_{\text{degurba3,Spedelec}} x_{\text{degurba==low}}\\&+ \beta_{\text{TT,Spedelec}} x_{\text{TT,Spedelec}}\\&+ \beta_{\text{cost}} x_{\text{cost,Spedelec}}\\&+ \beta_{\text{externalities,Spedelec}} \gamma_{\text{externalities by km,Spedelec}} x_{\text{distance,Spedelec}}\end{aligned} \tag{5.5}$$

Walk utility

$$\begin{aligned}U_{\text{walk}} &= \alpha_{\text{walk}}\\&+ \beta_{\text{female,walk}} x_{\text{sex==female}}\\&+ \beta_{\text{age,walk}} x_{\text{age}}\\&+ \beta_{\text{degurba2,walk}} x_{\text{degurba==medium}}\\&+ \beta_{\text{degurba3,walk}} x_{\text{degurba==low}}\\&+ \beta_{\text{TT,walk}} x_{\text{TT,walk}}\\&+ \beta_{\text{cost}} x_{\text{cost,walk}}\\&+ \beta_{\text{externalities,walk}} \gamma_{\text{externalities by km,walk}} x_{\text{distance,walk}}\end{aligned} \tag{5.6}$$

Table 5.3: Parameters of the mode choice model

Parameter	Explanation	Unit	Car	Public transport	Bicycle	E-Bike (Pedelec)	S-Pedelec	Walk
α_{m}	Constant	-	+0.31	−0.83	+1.45	-0.87	-1.4	+0.8
$\beta_{\text{female,m}}$	Dummy, Sex==Female	-	-	+0.31345	-0.03147	+0.32921	-0.363751	+0.07087
$\beta_{\text{age,m}}$	Age	years^{-1}	-	+0.00354	-0.02074	+0.00268	-0.026566	-0.00447
$\beta_{\text{degurba2,m}}$	Dummy, Density==Medium	-	-	-0.94476	-1.29194	-0.51416	-0.464518	-0.70167
$\beta_{\text{degurba3,m}}$	Dummy, Density==Low	-	-	-1.25242	-1.92303	-0.64266	-0.651147	-0.37095
$\beta_{\text{TT,m}}$	Travel time	hours^{-1}	-6.0	-2.0	-2.4	-2.0	-0.3	-2.0
$\beta_{\text{accessEgress,m}}$	Access+Egress time	hours^{-1}	-	-1.96973	-	-	-	-
$\beta_{\text{freq,m}}$	Headway	hours^{-1}	-	-0.50346	-	-	-	-
$\beta_{\text{cost,m}}$	Cost	CHF^{-1}	-0.06934	-0.06934	-	-	-	-0.06934
$\beta_{\text{ext,m}}$	Externalities	-	+0.644314	+1.44709	+3.18593	-	-	-
$\beta_{\text{extByKm,m}}$	Externalities by km	km^{-1}	+0.1601	+0.08	-0.0364	-	-	-

Table 5.4: Attribute calculations and surrogate values

Attribute	Definition
$x_{\text{degurba==medium}}$	Information about density not implemented, using surrogate value of 0.33
$x_{\text{degurba==low}}$	Information about density not implemented, using surrogate value of 0.33
$x_{\text{parking cost}}$	0 if the trip purpose is home or work. Otherwise, if the destination is within the city center, 4 CHF/hour; else, 2 CHF/hour. Since these details are unavailable in our implementation of the shortest paths, we globally assume 4 CHF for every car trip.
$x_{\text{cost,car}}$	0.188 CHF/km * $x_{\text{in-veh dist,car}}$
$x_{\text{in-veh dist,car}}$	Euclidean distance * a detour factor of 1.2
$x_{\text{cost,PT}}$	$x_{\text{cost,PT}} = \delta_{\text{hasAbo}} \times \frac{1}{2} \times \max 3.4, \delta_{\text{pt\_dist}\leq 5\text{km}} \times 0.89 \times x_{\text{pt\_dist}} + \delta_{\text{pt\_dist}\geq 5\text{km}} \times 0.589 \times x_{\text{pt\_dist}}$
δ_{hasAbo}	Not available in the accessibility calculation, using surrogate value of 0.5
$\delta_{\text{pt\_dist}}$	Euclidean distance * a detour factor of 1.5 (intentionally larger than the detour factor of car trips to account for longer detours in public transport)

5.4.6 Accessibility calculation

The accessibility calculation is inspired by the work presented in Geurs *et al.* (2010). Typically, logsum accessibility is part of the consumer surplus that considers all available destinations and modes and represents the result in monetary terms:

$$E(S_n) = (1/\alpha_n)\ln \sum_j \sum_m e^{V_{ijmn}} + C \qquad (5.7)$$

where i and j are origins and destinations, m is the mode, and n is the person. $e^{V_{ijmn}}$ is the systematic part of mode/destination travel utility (from i to j by mode m for person n) from mode and destination choice models. α_n is the marginal utility of income that converts the dimensionless utility values into monetary terms[4] and C is an unknown constant representing the fact that we can only measure differences in utility but not its absolute value.

In this work, we use a simplified approach focused on capturing the structure of accessibility changes. We remove the monetization, and instead of using a destination choice model, we scale the travel utility exponents directly with destination attraction values W_j (equal to number of full-time job equivalents from the STATENT dataset):

$$A_{i,n} = \ln \sum_j \sum_m e^{V_{ijmn}} * W_j + C \qquad (5.8)$$

Since we refrain from monetizing the effects, the results are referred to as "logsum accessibility" or "accessibility" rather than consumer surplus. The logsum accessibility values are calculated for each person, with their home location as a starting point and all jobs as destinations. We consider all modes described in Section 5.4.5, subject to availability restrictions (see Section 5.4.7).

Calculating the logsum accessibility for each origin requires the shortest paths to all possible destinations, using all available modes. To reduce the computational workload, we calculate the accessibility for a population sample: 100% of origin cells, 20% of the population within each cell, and 10% of all destination cells within 70 km. The destinations are sampled with the number of fulltime job equivalents as sampling weight to avoid overrepresenting cells with a log number of destinations. As a result, we obtain a sample size of 304'474 persons, each with approximately 2'800 destination cells. Note that the total population considered in this part is lower than the number of agents in 5.5 due to a smaller perimeter than in the case of the synthetic population. Given the choice between seven modes, calculating each shortest path separately would require computing roughly six billion hypothetical trips.

We use two strategies to further reduce the computational workload: First, we pre-calculate the shortest paths for an origin-destination matrix between the STATENT cells so that all shortest paths only need to be computed once for all individuals living within the same cell (100 x 100 meters). Second, we use one-to-many shortest path implementations that calculate all shortest paths from the same origin simultaneously.

The shortest paths by public transport were calculated using the `R5` package (Conway *et al.*, 2017) and the Python wrapper `r5py`[5] (Fink *et al.*, 2022), with the Swiss 2023 GTFS dataset[6]. For walking, cycling, and car trips, we used the one-to-many Dijkstra algorithm implementation in `networkx`[7] (Hagberg *et al.*, 2008), Unlike `R5`, it enables the direct use of pre-calculated edge weights without further adjustments throughout the process. In `R5`, we have provided the origin and destination coordi-

4 By definition, α_n is equal to $-\beta_{\text{cost}}$ from the (mode) choice model (McFadden, 1980). In this work, it results in $\alpha_n = 0.06934$

5 `https://github.com/r5py/r5py`

6 `https://opendata.swiss/en/dataset/timetable-2023-gtfs2020`

7 `https://github.com/networkx/networkx`

nates. In `networkx`, the shortest path is found between a pair of nodes in the street network. These are the closest points to the centroids of the origin and destination cells, accessible by the respective mode. The crowfly distance between the origin/destination points and those nodes is considered the access/egress walking distance, with an additional detour factor of 1.5[8].

Changes in accessibility are represented as a difference between the logsum accessibility "before" and "after":

$$\Delta A_{i,n} = A_{i,n}^{\text{after}} - A_{i,n}^{\text{before}} \tag{5.9}$$

This representation cancels out the unknown constant C. However, reporting the change in percent would be unreasonable since it would rely on meaningless reference values containing C. Therefore, we only calculate $\Delta A_{i,n}$ but no % change.

For every person in the sample, we calculate the change in their logsum accessibility for all modes together, as well as each mode separately. Then, the individuals are grouped into population groups based on their residential locations, age, sex, and driver's license ownership. The accessibility values before and after, and the differences, are aggregated as median values. Note that the median accessibility change across a group of individuals is not necessarily equal to a difference between their median accessibility values before and after.

To better compare effects that become undervalued in the medians, we also provide the same results with aggregation as means in Appendix D.

8 This value is higher than the detour factor for car trips used in U_{car} to account for longer detours on first-/last mile walking trip legs

5.4.7 Mobility tool ownership

During the accessibility calculation, we apply the same availability of modes as in the mode choice model estimation. This ensures a proper scaling of each mode in the resulting logsum accessibility. Cars are available for all individuals with a driver's license, and cycling modes are available for trips of up to 40 Kilometers. However, the population dataset used for the accessibility calculation does not contain information about driver's license ownership. Therefore, we identify drivers by drawing a random sample, containing 83% of individuals above 18 years of age (based on driver's license ownership in BFS and ARE (2023)). The ownership of cars and bicycles is not considered.

5.5 Results

5.5.1 Traffic volumes and mode shares

The simulation results show substantial changes in mode choice and total distance traveled. See Table 5.5 for a comprehensive report. Across the entire region, the total car kilometers traveled decreased by 3%. On the other hand, the total distance traveled on bicycles, pedelecs, and s-pedelecs increased by 13.4%, 22.7%, and 7.2%, respectively. Public transport usage increased by 9.5%. 5.6% of today's car drivers, or roughly 51'000 people, refrained from car use and mainly switched to public transport. While much of the change is a redistribution between modes, we also observed a net increase of the total distance traveled by 2%, or roughly 1.3 million pkm.

These effects are substantially larger in the city. For trips within the city, car kilometers traveled decreased by 10.2%. The number of car trips decreased even stronger, by 29.7%, suggesting substantially fewer first and last mile trips in residential areas. The distance traveled on bicycles, pedelecs, and s-pedelecs increased by 38.6%, 44.9%, and 44.4%. Roughly 30'000 or one quarter of today's drivers switch completely to other modes, primarily public transport. The total distance traveled increased by 16%. In the case of trucks with no alternatives in the simulation (no changes to logistics have been modeled), the total number of vehicle kilometers traveled increased by 41.9%

On trips crossing the city border, the number of car kilometers traveled decreased by 9.2% (or 18.6% of trips), while bicycle, pedelec, and s-pedelec usage increased by 42.9%, 56.3%, and 25.2%. The total distance traveled increased by 3%.

The maps in Figures 5.2, 5.3 and 5.4 show changes to traffic flows during the morning peak from 7:00 to 7:30. Figure 5.2 illustrates the substantial decrease of car traffic within the city and some increase on the highway (semi-)ring. However, it also shows that the one-way traffic regime on most streets and the capacity reduction led to more traffic on some streets, many inside residential areas. Figure 5.4 shows the future traffic flows. See Appendix D for maps with traffic flows in the off-peak time of 10:00-10:30.

Table 5.5: Mode shifts in the MATSim results

		All legs					Legs within the city					Cross-border legs				
State	Mode	N Agents	Distance (pkm)	%	Trips	%	N Agents	Distance (pkm)	%	Trips	%	N Agents	Distance (pkm)	%	Trips	%
Before	bike	265'233	2'135'178	3.6%	720'596	3.6%	52'116	316'177	9.7%	139'293	3.8%	16'878	332'867	2.0%	34'794	3.3%
	car	914'211	29'863'790	50.3%	2'672'171	13.4%	119'182	872'933	26.7%	262'796	7.3%	199'461	8'200'435	48.7%	421'474	39.5%
	car passenger	336'901	7'338'718	12.4%	684'214	3.4%	39'923	229'591	7.0%	71'456	2.0%	49'756	1'455'917	8.6%	85'071	8.0%
	ebike	42'184	632'652	1.1%	93'791	0.5%	7'243	56'156	1.7%	14'760	0.4%	6'334	164'216	1.0%	12'950	1.2%
	pt	501'803	12'740'527	21.4%	1'579'301	7.9%	151'364	829'145	25.4%	272'342	7.5%	183'464	5'927'479	35.2%	391'568	36.7%
	spedelec	1'767	42'426	0.1%	3'613	0.0%	146	884	0.0%	259	0.0%	291	11'511	0.1%	567	0.1%
	truck	60'063	1'541'689	2.6%	60'362	0.3%	3'950	17'388	0.5%	3'950	0.1%	17'035	421'644	2.5%	17'035	1.6%
	walk	2'273'741	5'115'629	8.6%	14'164'494	70.9%	683'050	946'411	29.0%	2'854'124	78.9%	60'460	333'297	2.0%	102'242	9.6%
After	bike	279'623	2'420'234	4.0%	773'322	3.9%	62'761	438'178	11.5%	173'157	4.8%	24'115	475'626	2.7%	50'501	4.7%
	car	863'070	28'980'879	47.8%	2'493'746	12.5%	88'767	783'955	20.6%	184'830	5.1%	164'905	7'448'608	42.9%	343'236	31.9%
	car passenger	336'825	7'610'570	12.5%	684'070	3.4%	39'949	342'307	9.0%	71'496	2.0%	49'800	1'578'984	9.1%	85'143	7.9%
	ebike	47'110	776'304	1.3%	107'796	0.5%	9'590	81'390	2.1%	20'049	0.6%	9'550	256'666	1.5%	19'861	1.8%
	pt	534'258	13'952'534	23.0%	1'709'006	8.5%	173'252	1'063'123	28.0%	317'838	8.8%	209'699	6'767'671	39.0%	447'366	41.6%
	spedelec	1'857	45'465	0.1%	3'816	0.0%	173	1'276	0.0%	309	0.0%	374	14'414	0.1%	733	0.1%
	truck	60'063	1'583'395	2.6%	60'362	0.3%	3'951	24'671	0.6%	3'951	0.1%	17'042	447'854	2.6%	17'042	1.6%
	walk	2'273'459	5'323'004	8.8%	14'175'603	70.9%	684'045	1'063'984	28.0%	2'853'226	78.7%	66'011	366'971	2.1%	111'503	10.4%
Diff Abs	bike	+14'390	+285'057		+52'726		+10'645	+122'001		+33'864		+7'237	+142'759		+15'707	
	car	-51'141	-882'911		-178'425		-30'415	-88'978		-77'966		-34'556	-751'827		-78'238	
	car passenger	-76	+271'852		-144		+26	+112'716		+40		+44	+123'066		+72	
	ebike	+4'926	+143'652		+14'005		+2'347	+25'233		+5'289		+3'216	+92'449		+6'911	
	pt	+32'455	+1'212'006		+129'705		+21'888	+233'977		+45'496		+26'235	+840'192		+55'798	
	spedelec	+90	+3'039		+203		+27	+393		+50		+83	+2'902		+166	
	truck	0	+41'705		0		+1	+7'283		+1		+7	+26'210		+7	
	walk	-282	+207'374		+11'109		+995	+117'573		-898		+5'551	+33'673		+9'261	
Diff %	bike	+5.4%	+13.4%		+7.3%		+20.4%	+38.6%		+24.3%		+42.9%	+42.9%		+45.1%	
	car	-5.6%	-3.0%		-6.7%		-25.5%	-10.2%		-29.7%		-17.3%	-9.2%		-18.6%	
	car passenger	-0.0%	+3.7%		-0.0%		+0.1%	+49.1%		+0.1%		+0.1%	+8.5%		+0.1%	
	ebike	+11.7%	+22.7%		+14.9%		+32.4%	+44.9%		+35.8%		+50.8%	+56.3%		+53.4%	
	pt	+6.5%	+9.5%		+8.2%		+14.5%	+28.2%		+16.7%		+14.3%	+14.2%		+14.2%	
	spedelec	+5.1%	+7.2%		+5.6%		+18.5%	+44.4%		+19.3%		+28.5%	+25.2%		+29.3%	
	truck	0.0%	+2.7%		0.0%		+0.0%	+41.9%		+0.0%		+0.0%	+6.2%		+0.0%	
	walk	-0.0%	+4.1%		+0.1%		+0.1%	+12.4%		-0.0%		+9.2%	+10.1%		+9.1%	

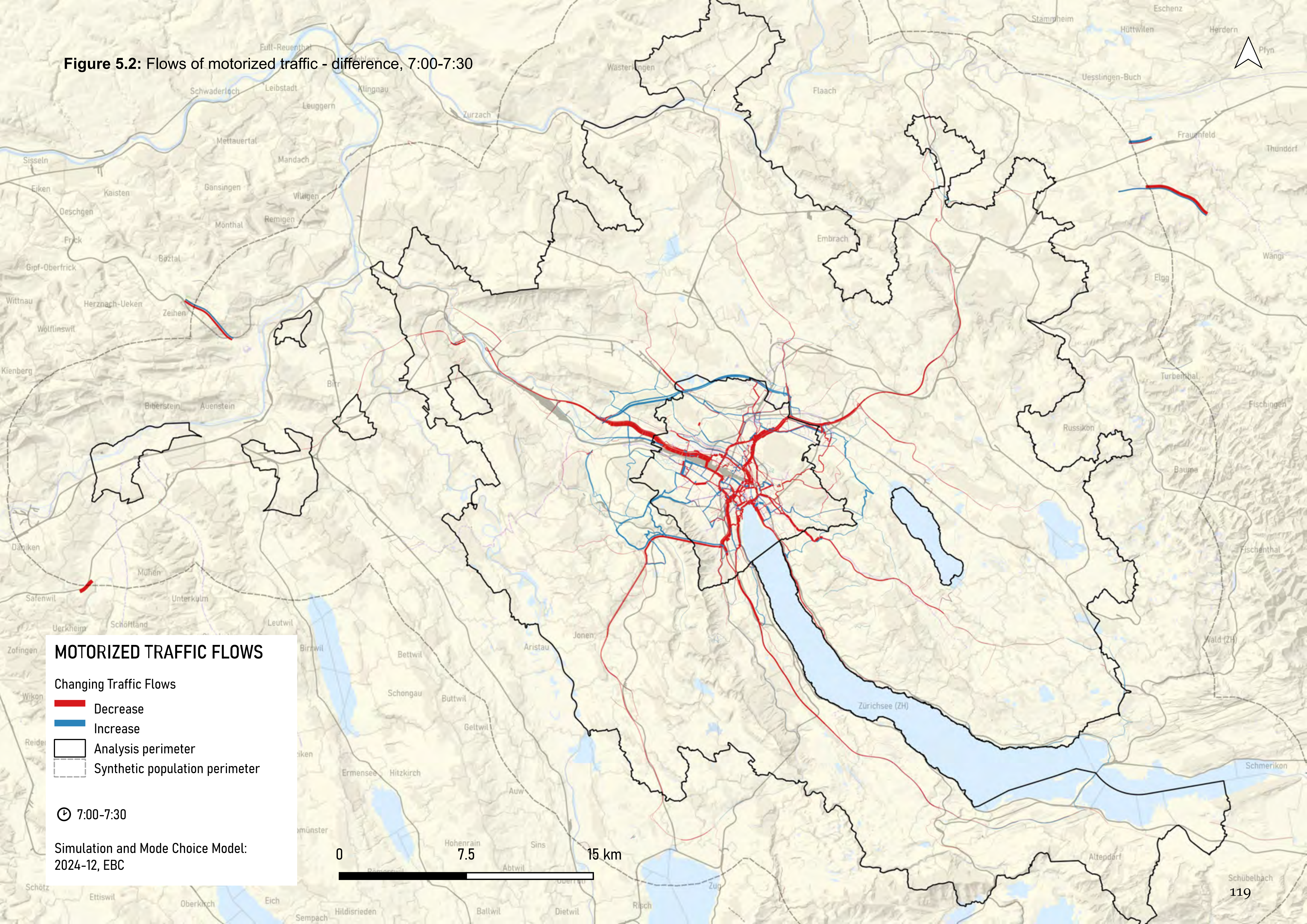
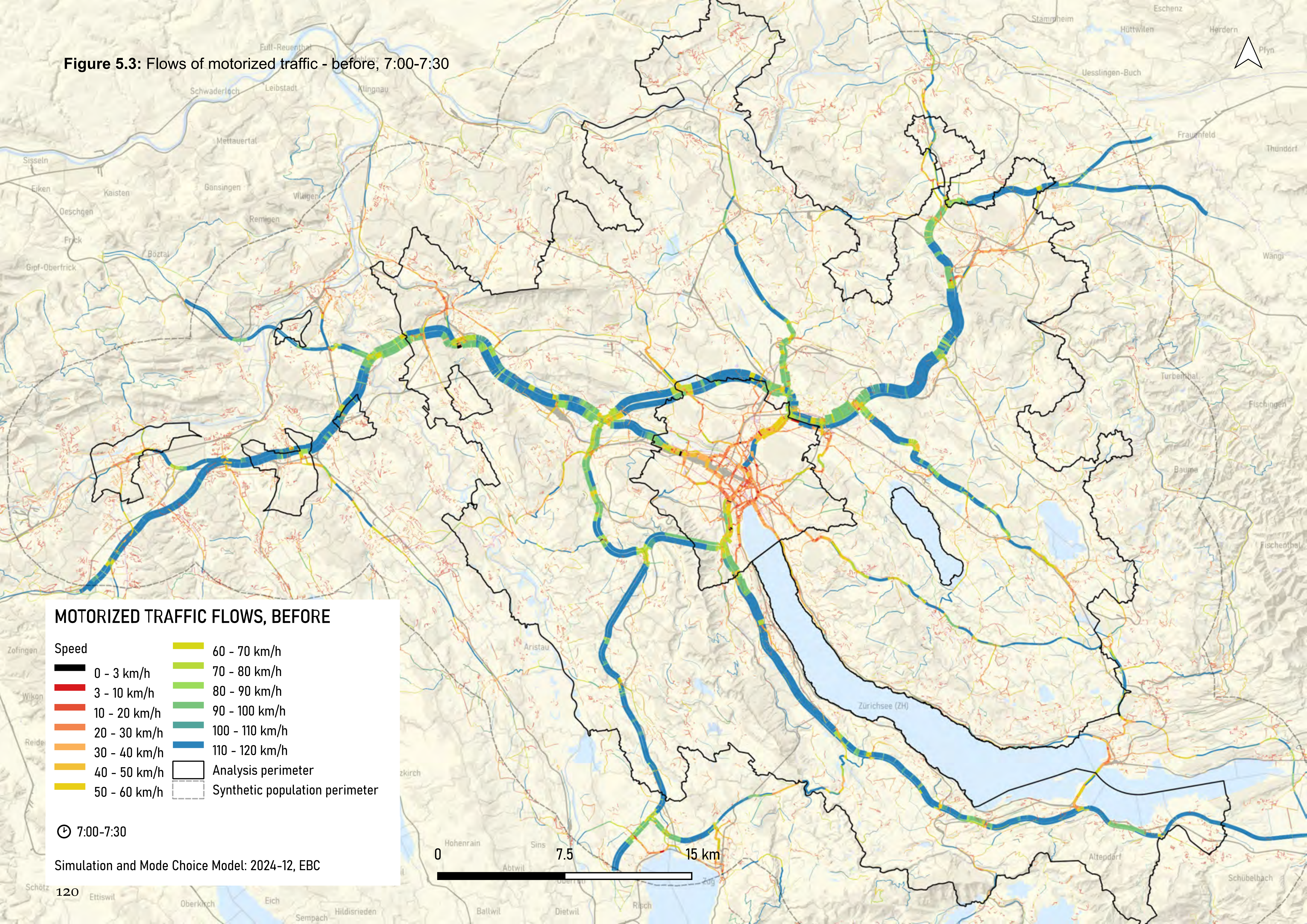


Figure 5.2: Flows of motorized traffic - difference, 7:00-7:30

Figure 5.3: Flows of motorized traffic - before, 7:00-7:30



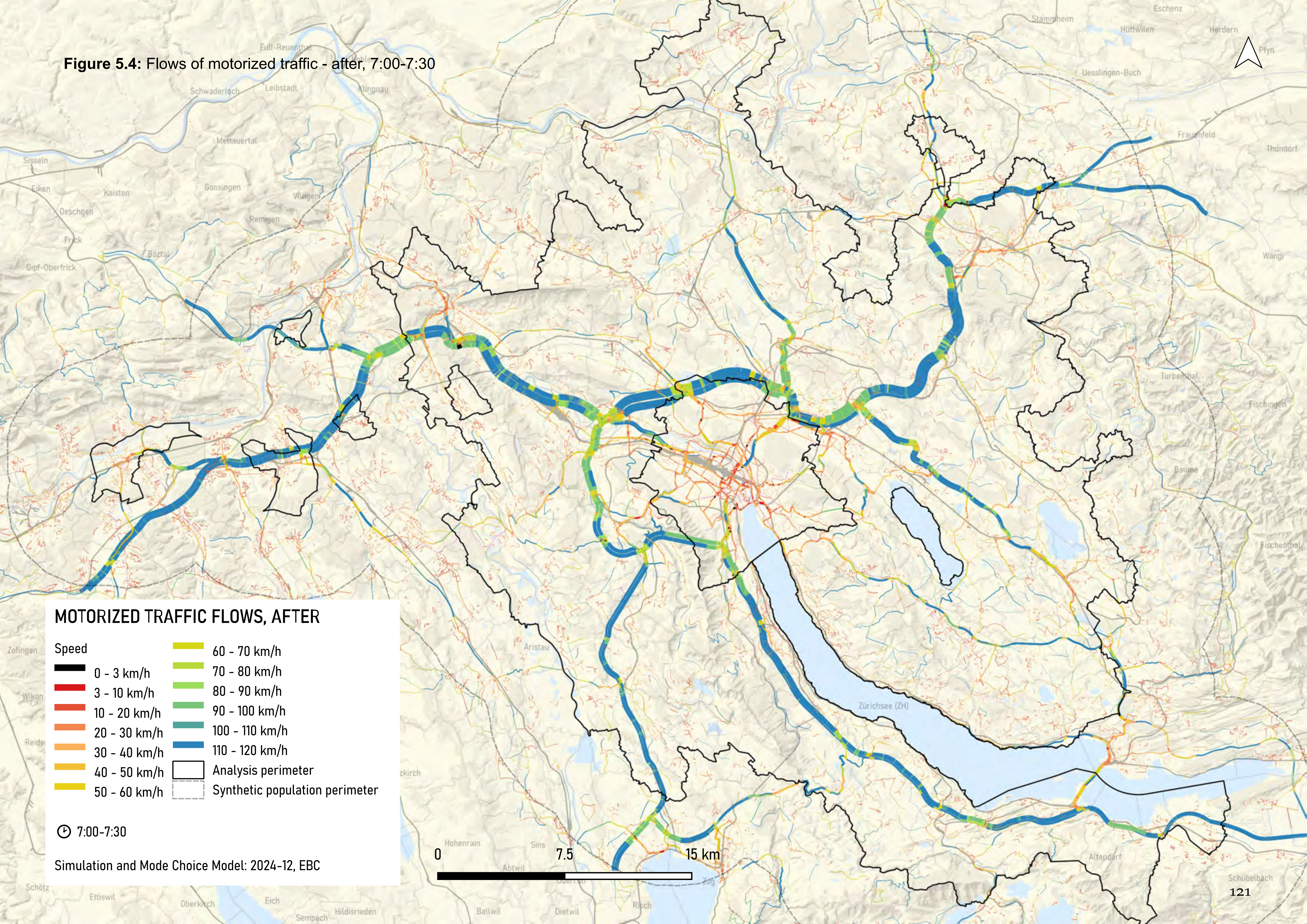


Figure 5.4: Flows of motorized traffic - after, 7:00-7:30

5.5.2 Losgum accessibility

In this section, we report the accessibility changes during the morning peak time of 7:00-7:30. Table 5.6 shows the results for the city of Zurich and the rest of the analysis perimeter. Across the entire region, we observed an accessibility increase for the cycling modes and a decrease for car trips. Those using a bicycle, pedelec, or s-pedelec within the city experienced an accessibility increase of 0.211, 0.086, and 0.015 utility points, respectively. On the other hand, those using a car incurred a loss of 0.411. Considering all modes together, the total accessibility change within the city is -0.058 for those with access to a car and +0.091 for those without a car.

The effects are additionally accentuated in Zurich's high-density urban neighborhood Seefeld, shown in Table 5.7. The cycling accessibility increased by roughly 0.264, while the car accessibility decreased by 0.985. Outside the city, the changes are weaker, with slight accessibility gains on bicycles, pedelecs, and s-pedelecs of 0.136, 0.077, and 0.015 and car accessibility losses of 0.178. Across the entire analysis perimeter, the total accessibility decreased by 0.026 utility points. Public transport and walking accessibility remain unchanged since we assumed no changes to schedules and pedestrian infrastructure.

The cycling accessibility gains within the city are slightly higher for individuals 60+ years of age, non-drivers, and females, compared to their counterparts. Outside the city, the cycling accessibility gains are roughly the same for all groups.

The maps in Figures 5.5 - 5.7 show the accessibility changes in space. In large parts of the city, car accessibility decreased by more than 0.35 utility points, except in the city center, which experienced only a relatively small change. Outside the city, the areas to the east experienced slight accessibility reductions, while one region to the west obtained an accessibility gain. Cycling accessibility, on the other hand, increased across much of the area. The most substantial increase is observed at the city borders and along the eastern lake shore. Similar to car accessibility, the changes in the city center are relatively small. This can be explained by spatial disparities in the added cycling infrastructure and its benefits. While in the central areas, possibilities for adding cycling infrastructure are heavily restricted by tightly limited road space, pedestrian zones, and many public transport services, these restrictions are substantially weaker toward the city borders. Furthermore, the proportion of roads with already existing cycling infrastructure tends to be higher in busier areas, and thus, adding further cycling paths has a lower impact (in our model) than on the peripheries.

The overall accessibility decreased slightly in the city and parts of the larger region. However, despite large disparities in changes of cycling and car accessibility, the overall change is substantially smaller and more equally distributed, rarely exceeding the range of -0.15 to +0.15 utility points. In most areas, we observe a mixture of gains for non-drivers and losses for drivers. In the western part of the perimeter, both drivers and non-drivers obtained accessibility gains. A few small areas in the city with large accessibility losses indicate local network issues (such as long detours or capacity bottlenecks) created by the network generation algorithm. Nevertheless, their impact on the results reported in Table 5.6 is negligible due to the nature of median aggregation.

Table 5.6: Median logsum accessibility changes, 7:00-7:30

		Entire Region excl. City of Zurich							City of Zurich							
		Age			Car		Sex		Age			Car		Sex		
State	Mode	Other	≤25	≥60	Non-Drivers	Drivers	Female	Male	Other	≤25	≥60	Non-Drivers	Drivers	Female	Male	All
Sample		110′025	59′412	50′430	70′249	149′618	109′890	109′977	46′197	20′125	15′451	24′423	57′350	40′917	40′856	304′474
Before	Cars	12.190	-inf	12.167	-inf	12.257	12.064	12.064	12.137	-inf	12.105	-inf	12.165	12.080	12.086	12.068
	PT	10.984	10.860	11.108	10.905	11.010	11.145	10.809	10.982	10.826	11.059	10.886	10.986	11.109	10.803	10.974
	Cycling	9.656	10.244	8.979	9.994	9.518	9.616	9.695	11.338	11.837	10.573	11.639	11.241	11.302	11.387	10.103
	Pedelec	11.178	11.087	11.249	11.124	11.191	11.326	10.997	11.751	11.675	11.907	11.731	11.780	11.959	11.628	11.360
	S-Pedelec	10.278	11.072	9.491	10.916	10.156	10.106	10.513	10.472	11.161	9.566	10.978	10.403	10.333	10.725	10.376
	Foot	8.258	8.359	8.044	8.295	8.210	8.261	8.212	11.251	11.215	10.950	11.197	11.177	11.199	11.168	8.844
After	Cars	12.011	-inf	12.000	-inf	12.090	11.883	11.879	11.672	-inf	11.623	-inf	11.735	11.560	11.574	11.744
	PT	10.984	10.860	11.108	10.905	11.010	11.145	10.809	10.982	10.826	11.059	10.886	10.986	11.109	10.803	10.974
	Cycling	9.777	10.359	9.094	10.123	9.647	9.749	9.828	11.552	12.057	10.810	11.878	11.475	11.535	11.609	10.274
	Pedelec	11.262	11.171	11.331	11.208	11.275	11.409	11.080	11.829	11.755	12.029	11.828	11.879	12.050	11.717	11.453
	S-Pedelec	10.294	11.088	9.508	10.932	10.172	10.123	10.529	10.487	11.178	9.582	10.995	10.419	10.348	10.739	10.392
	Foot	8.258	8.359	8.044	8.295	8.210	8.261	8.212	11.251	11.215	10.950	11.197	11.177	11.199	11.168	8.844
Diff	Cars[a]	-0.179	-0.181	-0.174	-	-0.178	-0.178	-0.178	-0.413	-0.403	-0.408	-	-0.411	-0.412	-0.410	-0.219
	PT	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
	Cycling	+0.137	+0.136	+0.135	+0.137	+0.136	+0.136	+0.137	+0.206	+0.219	+0.228	+0.216	+0.211	+0.214	+0.211	+0.155
	Pedelec	+0.077	+0.077	+0.076	+0.077	+0.077	+0.077	+0.077	+0.084	+0.090	+0.093	+0.089	+0.086	+0.088	+0.086	+0.081
	S-Pedelec	+0.015	+0.015	+0.015	+0.015	+0.015	+0.015	+0.015	+0.015	+0.016	+0.016	+0.016	+0.015	+0.015	+0.015	+0.015
	Foot	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Before	All	12.909	12.623	12.857	12.406	12.964	12.884	12.785	13.218	13.169	13.087	12.973	13.245	13.219	13.143	12.946
After	All	12.857	12.671	12.802	12.463	12.912	12.846	12.744	13.174	13.219	13.015	13.072	13.183	13.194	13.113	12.915
Diff	All	-0.038	+0.028	-0.041	+0.045	-0.049	-0.021	-0.027	-0.045	+0.081	-0.062	+0.091	-0.058	-0.030	-0.038	-0.026

a Difference in car accessibility includes only individuals with a driver's license

Table 5.7: Median logsum accessibility changes for Seefeld, 7:00-7:30

		Seefeld						
		Age			Car		Sex	
State	Mode	Other	≤25	≥60	Non-Drivers	Drivers	Female	Male
Sample		1'298	415	420	593	1'540	1'107	1'026
Before	Cars	11.890	-inf	11.886	-inf	11.915	11.859	11.861
	PT	11.278	11.195	11.392	11.216	11.296	11.378	11.060
	Cycling	11.324	11.869	10.655	11.603	11.251	11.305	11.351
	Pedelec	11.863	11.803	11.966	11.801	11.870	11.946	11.615
	S-Pedelec	10.444	11.185	9.567	10.868	10.364	10.303	10.649
	Foot	11.341	11.482	11.179	11.400	11.321	11.369	11.306
After	Cars	10.808	-inf	10.864	-inf	10.874	10.782	10.774
	PT	11.278	11.195	11.392	11.216	11.296	11.378	11.060
	Cycling	11.586	12.131	10.923	11.835	11.515	11.571	11.602
	Pedelec	11.993	11.931	12.095	11.928	11.996	12.059	11.728
	S-Pedelec	10.460	11.204	9.583	10.885	10.381	10.322	10.666
	Foot	11.341	11.482	11.179	11.400	11.321	11.369	11.306
Diff	Cars[a]	-1.007	-0.955	-0.975	-	-0.985	-0.985	-1.051
	PT	0.000	0.000	0.000	0.000	0.000	0.000	0.000
	Cycling	+0.264	+0.249	+0.267	+0.264	+0.264	+0.264	+0.264
	Pedelec	+0.115	+0.112	+0.116	+0.115	+0.115	+0.115	+0.113
	S-Pedelec	+0.017	+0.017	+0.018	+0.017	+0.017	+0.018	+0.017
	Foot	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Before	All	13.211	13.232	13.139	13.040	13.227	13.242	13.147
After	All	13.123	13.282	13.025	13.140	13.129	13.181	13.062
Diff	All	-0.085	+0.098	-0.116	+0.101	-0.102	-0.071	-0.088

a Difference in car accessibility includes only individuals with a driver's license

Figure 5.5: Logsum accessibility changes on car trips, 7:00-7:30

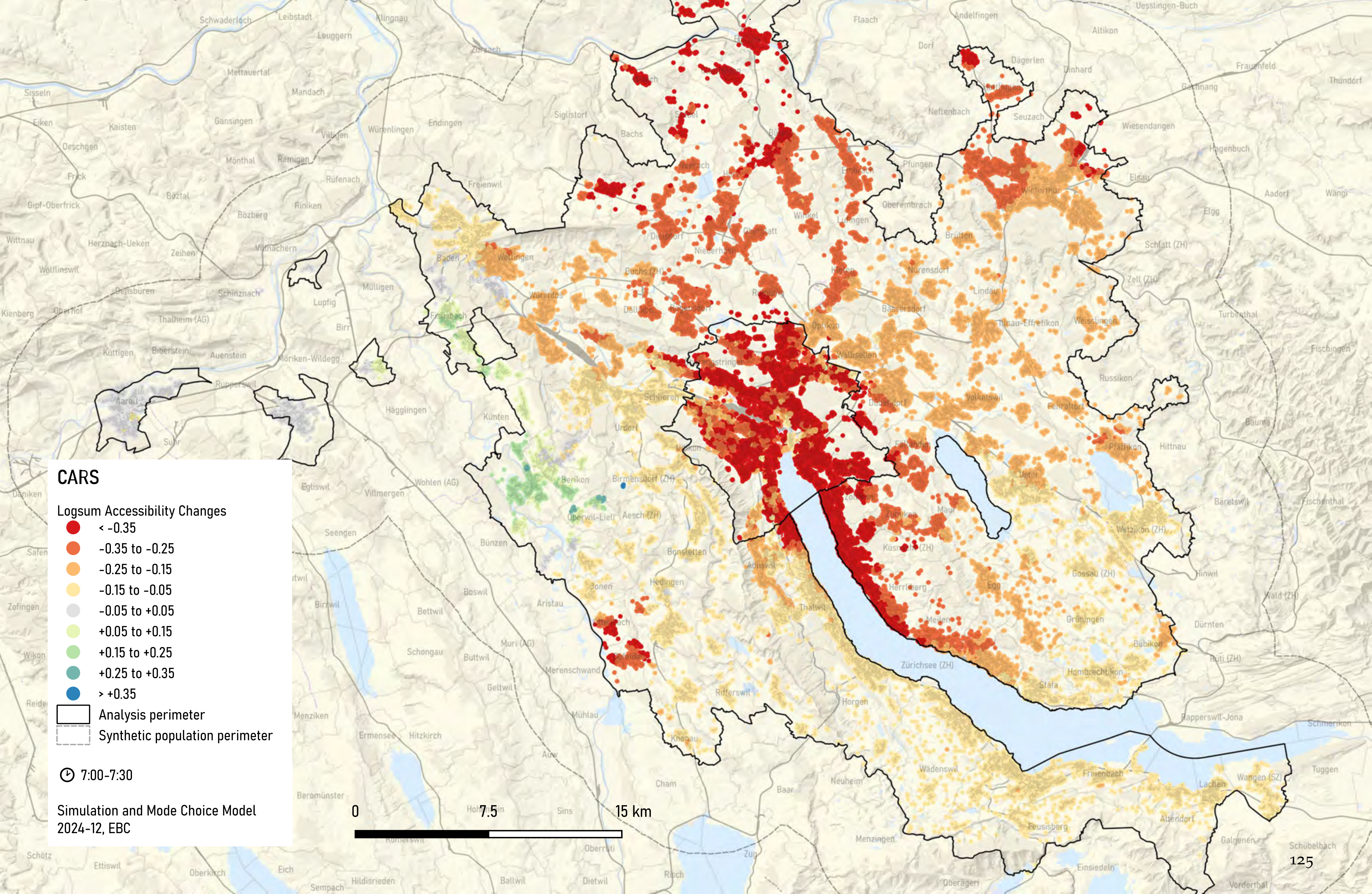


Figure 5.6: Logsum accessibility changes on cycling trips

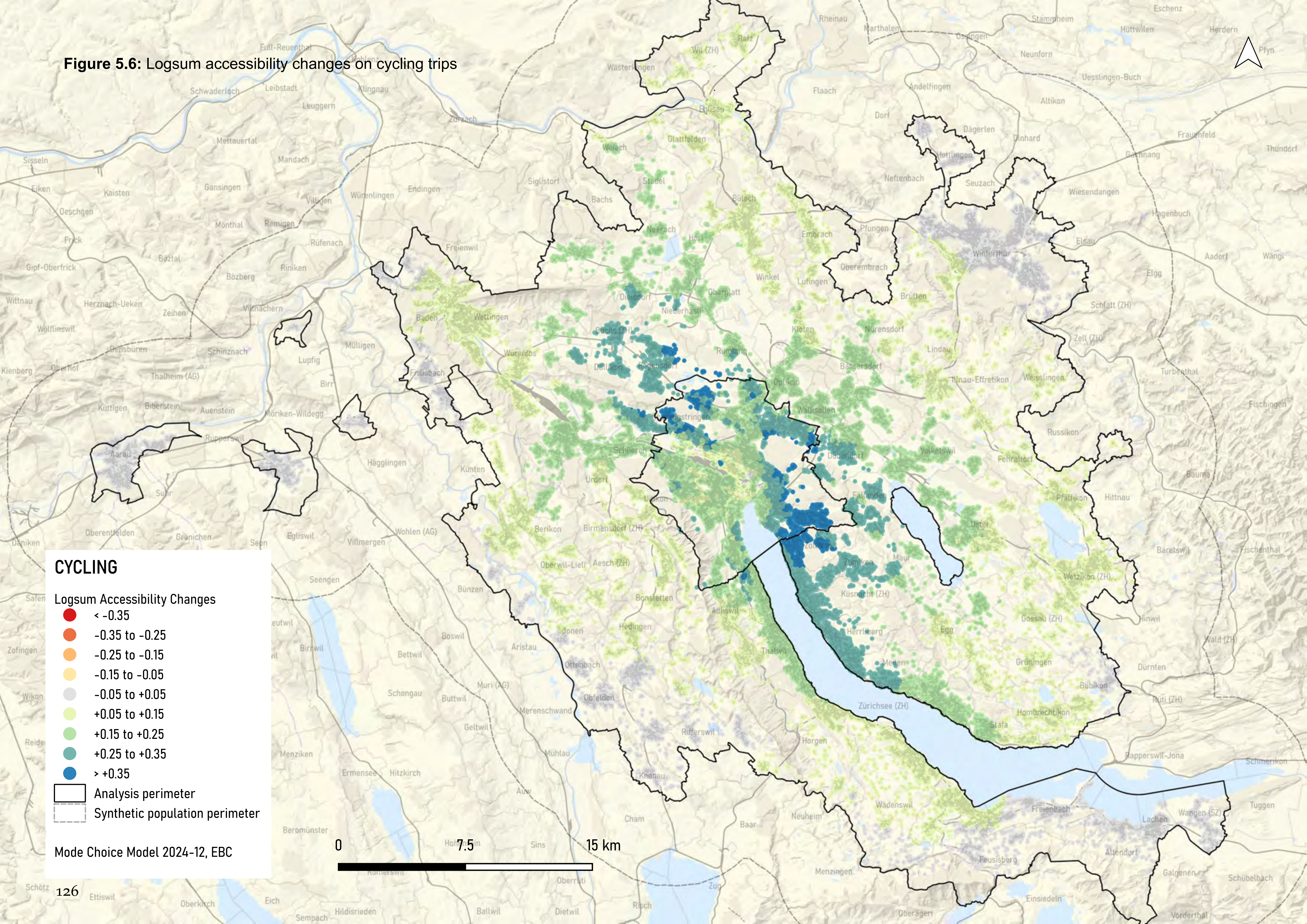
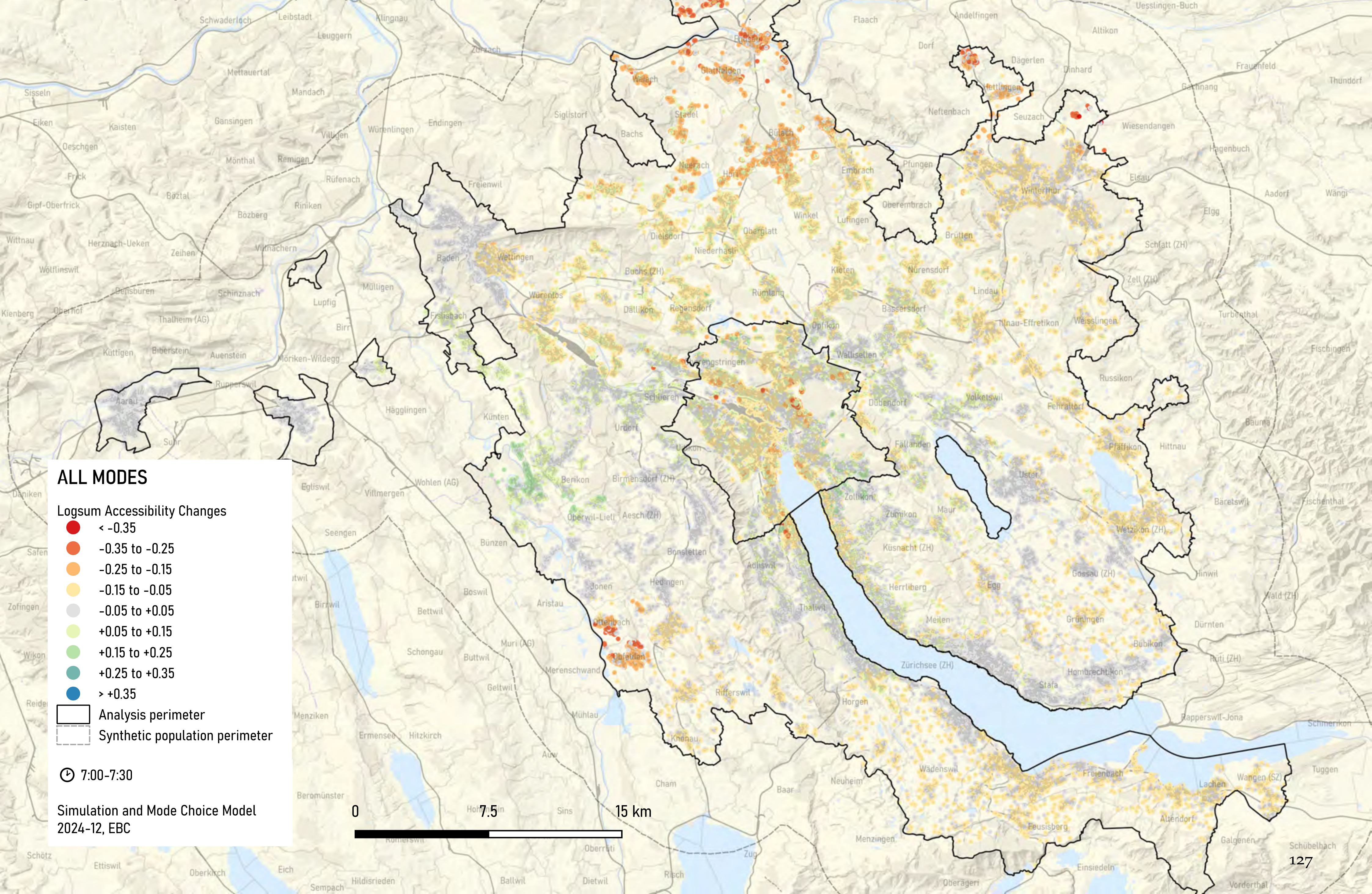


Figure 5.7: Logsum accessibility changes including all modes, 7:00-7:30



5.6 Equity effects

Chapter 2 has elaborated on the possible distributive effects of the E-Bike City, considering a few different population groups. Table 2.1 has provided conceptual relationships between expected accessibility levels and their changes among drivers and non-drivers inside and outside the city. In this section, we revisit the original idea and validate it using the above accessibility results. We use the same population groups with their respective median accessibility values from the previous section. The results are reported in Table 5.8, in a similar format as in Chapter 2. We apply Z-scores to rank the results within the entire population. For absolute levels, we use the status quo values as reference values. For differences, the reference values are derived from the accessibility change across all individuals (see the last three columns of the table).

Currently, the population group experiencing the lowest accessibility levels are non-drivers living outside the city. On the other hand, the drivers inside the city have the highest accessibility levels. The non-drivers in the city have slightly higher accessibility levels than drivers in the suburban areas, but they are roughly comparable. With the E-Bike City transformation, urban non-drivers experienced the largest accessibility gains, and urban drivers incurred the largest losses. The gains and losses of suburban residents have the same direction but smaller magnitudes. The accessibility ranking among the groups remained unchanged, with the highest accessibility enjoyed by urban drivers and the lowest by suburban non-drivers. However, the disparities between the groups decreased massively, especially between urban drivers and non-drivers.

Further, we study the distribution of accessibility changes over current accessibility levels. Figure 5.8 shows the median accessibility change for each decile of $A_{i,n}^{\text{before}}$, considering the accessibility across all modes and for each mode separately. The overall accessibility gains are concentrated among groups in the lowest two accessibility deciles, while the highest losses were experienced by those with the highest accessibility.

However, considering individual modes separately, the distributive effects are reversed. Within cycling, the largest gains are observed among the groups that already enjoy the highest cycling accessibility. Similarly, among drivers, those with the lowest accessibility incurred the largest losses, while those in the highest deciles of $A_i, n, \text{car}^{\text{before}}$ experienced slightly smaller losses. The distributive effects within pedelecs and s-pedelecs are rather small and do not show any substantial disparities between accessibility deciles. The distribution of cycling accessibility can be explained by the spatial limits of the transformation that roughly correspond with urban areas with a high density of destinations and already a relatively high density of cycling infrastructure. In the case of car accessibility, the effects are less intuitive. Unlike in cycling infrastructure, where the benefits are mostly local, the resulting congestion in motorized traffic can impact accessibility over long distances. Figure 5.5 shows that remote areas at the northern end of the perimeter experienced larger car accessibility losses than areas closer to the city. These relatively strong impacts in remote areas outside the city are likely the cause of the inverse distributive pattern in car accessibility.

Comparing the distributive effects in car and bicycle accessibility to those with all modes seemingly reveals a contradiction: While in the case of bicycles and cars, the accessibility disparities have increased, the overall accessibility shows decreasing disparities (also in 5.8). This paradox can be explained by the driver's license ownership that produces a systematic disparity between drivers and non-drivers. While the former group experiences higher accessibility levels and mostly accessibility losses, the effects are the opposite in the case of the second group.

Figure 5.8: Median accessibility changes by decile

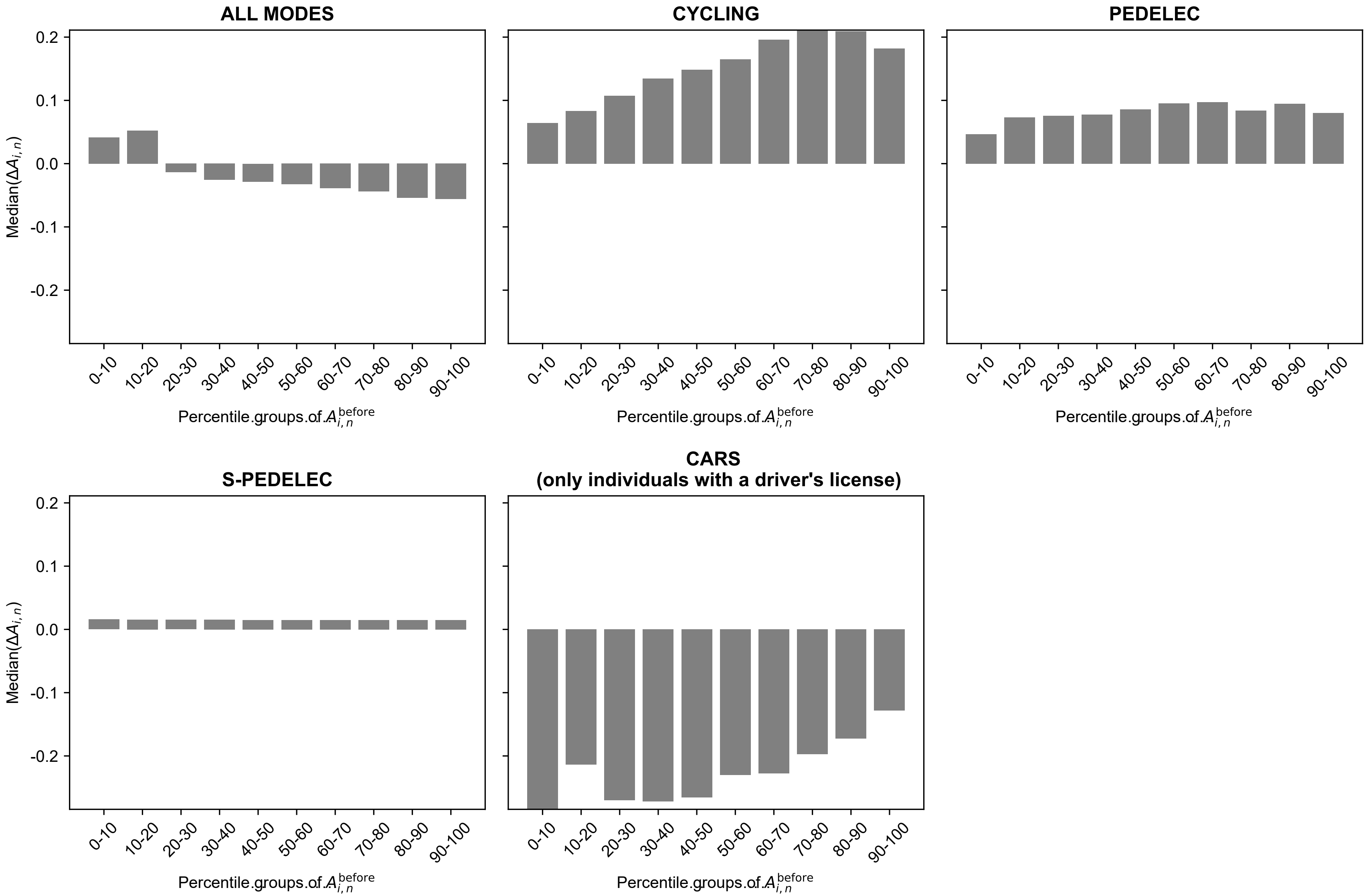


Table 5.8: Equity effects in the morning peak (Z-Scores of median accessibility values and median changes)

	City Residents		Suburban Residents				
	Non-Drivers	Drivers	Non-Drivers	Drivers	Reference values	μ	ρ
Before	+0.25	+0.91	-1.13	+0.22	Before, all	+12.8921	0.4354
After	+0.49	+0.76	-1.00	+0.10	Before, all	+12.8921	0.4354
Difference	+1.46	-0.49	+0.86	-0.38	Diff, all	-0.0204	0.0759

5.7 Discussion

Reorganizing the transport network to favor dedicated cycling infrastructure has substantially shifted the mode choice from cars to public transport and cycling. This effect is seen within the city and, to a smaller extent, across the entire region. Given today's load factors in parts of the public transport system during peak times, an E-Bike City conversion would make it necessary to invest in capacity increases. Moreover, while the number of kilometers traveled by car decreased, the distance traveled by other modes increased by more than twice as much. The effect is even stronger when considering only cross-border trips or those within the city. It can be explained by larger detours for the remaining car trips created by the one-way streets (see Table 3.4 for the detour indicators) and by mode shifts to public transport services requiring longer detours for reasonable demand bundling. However, in the long run, these effects can be expected to weaken due to changes in destination choice, mobility tool ownership, and new, more direct public transport services that become financially viable with the higher demand.

The accessibility increased for cycling trips and decreased for car trips. Considering all modes together, the effects are substantially smaller and more regularly distributed over space than in the case of individual modes. Nevertheless, accessibility increased for non-drivers and decreased for drivers. Overall, the median accessibility change was negative. However, the resulting accessibility effects can be further improved by refining the network design, considering long-term behavior changes, and adding further policy measures like changes to public transport or land use changes.

Considering each mode separately, the E-Bike city transformation has created the largest improvements for those with the highest accessibility levels (cycling) and the largest losses for those with the lowest accessibility (cars). However, considering all modes together, the pattern is reversed, reducing disparities between the lowest and highest accessibility levels. The E-Bike City promotes transport justice, mainly due to a redistribution from drivers to non-drivers. These findings also highlight the benefit of using a multimodal logsum measure over simpler accessibility measures that can only be considered for each mode separately.

The benefits of cycling infrastructure rely heavily on the value of distance indicators from Meister *et al.* (2023). Rooted in the random utility theory, they offer a theoretical consistency with an overarching framework of discrete mode choice models and logsum accessibility, unlike an alternative approach based on Levels of Traffic Stress (LTS, see Furth *et al.* (2016), Fässler (2017)). However, while the logsum approach is theoretically more robust, our implementation is subject to practical limitations. First, it does not distinguish between types of cycling infrastructure. While in reality, converting the many narrow cycling lanes into wide cycling paths would certainly create benefits for cyclists, the current model does not capture the difference. Moreover, it does not consider traffic volumes, thus assigning the same benefits to separated cycling infrastructure independently of car traffic volumes. In reality, many residential streets with low car traffic volumes already provide a similar level of cycling comfort as separated paths. As a result, our model tends to underestimate the benefits of the better cycling paths in areas with heavy traffic and already existing narrow cycling lanes. Simultaneously, it overestimates the benefits of added cycling infrastructure on residential roads with low car traffic volumes. While in Section 5.5.2, we have described the pattern of high cycling accessibility gains toward the city borders, adding a differentiation among cycling infrastructure types and by car traffic volumes would likely reduce this effect.

Further, the effects reported for e-bikes are relatively small compared to conventional bicycles. For example, in the case of s-pedelecs, the distributive effects in 5.8 allow no useful conclusions. The small effects are likely rooted in the design of the current mode choice model that does not consider the limited ownership of these vehicles. To reproduce their small mode shares in today's transport system, their utility functions must assume low utility values, leading to small effects in the resulting accessibility changes. Therefore, we have restricted most conclusions to cars and conventional bicycles.

Finally, our modeling approach relies on limiting assumptions about behavior. The logsum measure assumes that individuals seamlessly adjust to new choice situations, changing modes (and destinations) according to the same preferences as they had when making their current choices. It is optimistic in ignoring captivity or long-term obligations toward specific lifestyles. However, at the same time, it is pessimistic in assuming today's behavior without long-term changes to demography, mobility tool ownership, and general attitudes toward mobility choices. The large changes proposed in the E-Bike City concept, however, may also lead to shifts in car and bicycle ownership, as well as cultural changes (see te Brömmelstroet *et al.* (2020)) that will shape future behavior in ways far beyond today's behavior.

5.8 Conclusions and further work

We have shown that the E-Bike City can reduce total car traffic and reduce accessibility disparities. Overall, the accessibility improvements in cycling did not compensate for the accessibility losses in car traffic, resulting in the median accessibility change being negative. However, the overall balance can be improved by combining the E-Bike City with other policy changes like reorganizing the public transport services or introducing road pricing. Moreover, a further development of the network design methodology and refining the effects considered in the impact assessment may yield further improvements in the overall accessibility levels.

The results reported are subject to several limitations. First, we have assumed today's behavior and neglected any long-term adaptations to mobility tool ownership, demography, land use, or cultural values. Second, the cycling infrastructure benefits considered are limited by the availability of empirical evidence in the underlying route choice model. Including car traffic volumes (comparable to the LTS approach) and distinguishing between types of cycling infrastructure would enable a higher accuracy of the reported effects. Third, limitations in the network design methodology may lead to underestimating the theoretical potential of the transformation. Improving the design process may produce networks with better combinations of cycling and car accessibility. Finally, we have not considered further policy measures that may enhance the overall effects.

Future research should explore the economic effects of such a transformation over time while considering long-term changes, including destination choices, mobility tool ownership, and land-use patterns. A refined mode choice model should improve the assumptions about mobility tool ownership, allowing for stronger effects to be observed, particularly for e-bikes. Advancing the field of network design and optimization (e.g., Wiedemann *et al.* (2025); Szell *et al.* (2022); Steinacker *et al.* (2022); Paulsen and Rich (2023)) could enhance future designs. Especially, integrating the mathematical optimization approach introduced in Wiedemann *et al.* (2025) into the multimodal design process of `snman` has the potential to create optimal designs that also consider real-life restrictions related to parking and public transport. Additionally, incorporating other policy measures, such as road pricing, changes to public transport services, and land-use changes, could provide a more comprehensive understanding of the potential impacts of an E-Bike City transformation.

The E-Bike City transformation presents a viable strategy for promoting sustainable and more equitable urban mobility. We have shown that it supports a shift toward more sustainable and space-efficient travel modes while reducing the disparities between individuals with the highest and the lowest accessibility levels. However, further research is needed to refine its design and understand its long-term economic, social, and environmental impacts. A comprehensive approach that integrates additional policy measures and considers behavioral adaptations will be key to maximizing the potential of this transformation.

Chapter 6: Conclusion and Outlook

This dissertation has discussed a possible shift from the ”large infrastructure” paradigm to one based on ”small infrastructure”. To provide a tangible example of such a shift, it has expanded the idea of an E-Bike City by asking how it would work in Zurich.

To answer this question, the thesis has theorized the original idea into a functional concept, provided a design for Zurich's network, streets, and intersections, and evaluated the expected impacts. The following sections reflect on the detailed research questions addressed in each chapter.

6.1 The concept of an E-Bike City

Chapter 2 has addressed how to design the E-Bike City as a new starting point for transport policy discussions. It developed the early ideas in Axhausen (2022) into a functional concept rooted in a wide array of literature. Also, it proposed a series of research questions, some of which were addressed in the subsequent chapters.

On the other hand, the concept has a couple of limitations. First, it omits transition pathways, which is especially important in low-density areas where decades of car dependency are reflected in land-use patterns that are difficult to serve by other modes. Second, the concept has not touched substantially on the social significance of transport modes and possible resistance to change resulting from factors other than a purely rational choice.

These limitations translate into directions for future research. Further studies can focus on transition pathways in traditionally car-oriented environments and possible equity effects that emerge during the intermediary stages. Further work is also needed to understand the limits of people's willingness to make such shifts for reasons beyond a pure rationality of choice. And finally, making concepts like the E-Bike City scalable to other places will require localized alternatives aligned with traditions in different regions. This applies especially in the global south while avoiding an uncritical transfer of ”best practices” from Europe (see De Satgé and Watson (2018); Castañeda (2021)).

6.2 Rapid and reproducible design of alternative transport networks

Exploring new transport planning paradigms is crucial for identifying future pathways in otherwise slowly moving transport policy discussions. However, modeling and testing such completely alternative futures manually is tedious. Such an approach also risks credibility loss due to personal judgment applied during the design. Algorithms for generating alternative transportation networks automatically and transparently are bridging this gap. However, the existing solutions have not been able to produce complete scenarios of allocating road space across entire cities.

The research question addressed in Chapter 3 was how to model the E-Bike City (and possibly other transport planning paradigms) rapidly and reproducibly. The chapter has introduced an automated design process and the open-source Python package `snman`, allowing planners to carry out such design exercises in any city worldwide. It also shows a design for Zurich and estimates the theoretical potential for change.

The design was created to maximize the proportion of road space allocated to cycling paths. The road widths remained unchanged (i.e., no streets were added, widened, or removed), all buildings had to remain accessible by car within walking distance, and all public transport services must still be able to operate along their existing routes and maintain the same level of separation from other modes.

The proportion of road space allocated to cycling infrastructure increased by a factor of 4.5, from 12.1% to 54.3%. On the other hand, the proportion of space for general travel lanes decreased by roughly one-half, from 66.6% to 35.1%. Car traffic capacity decreased substantially, and drivers incurred an additional average detour on car trips of 35.7%. In exchange, the generalized cost of average cycling trips decreased by 24.1%.

The automated design process can produce holistic network designs for entire cities. It considers the limited road space, as well as numerous constraints that make up a functioning network for car traffic, cycling, and public transport. The results of the alternative network design in Zurich illustrate that large changes in road space allocation are possible even while maintaining basic car access and a high-quality public transport service. It shows a future where changes in accessibility are produced differently than through large, high-profile pieces of infrastructure and high maximum speeds. The resulting network is used in Chapter 5 for evaluating the impacts of the E-Bike City.

While the chosen approach succeeds at generating complete designs, several shortcomings have not been addressed yet. First, the design process relies on graph-theory heuristics, without demand data, and is steered by several parameters and design rules. A mathematical optimization would allow a more flexible generation of networks, steered by precisely defined objective functions related to travel demand. A notable step in this direction in Wiedemann *et al.* (2025) already optimizes travel lanes and cycling infrastructure. However, further work is needed to allow complete multimodal networks, including public transport and parking spaces. Such an optimization-based approach can be integrated with MATSim or Eqasim (Hörl and Balac, 2021) as an iterative process where the networks are optimized based on a transport simulation that contains discrete route-, mode-, and destination choice models.

Second, the network redesign is restricted to the municipal area of the city, without any measures in the suburban areas. For an effective mobility transition, future work must show how to extend the concept into lower-density suburban areas.

Third, the allocation of cycling infrastructure is opportunistic rather than aiming for a specific network. The design for Zurich allows a provision of cycling infrastructure on almost every street. Thus, there is no urgent need for such a strategic network plan. However, in less extensive redesigns, this approach must be supplemented with a structured method for channeling cycling infrastructure into a cohesive network rather than placing it opportunistically.

Fourth, the design process lacks a phased implementation strategy, similar to the limitations outlined in Chapter 2. To support real-world applications, future development is needed to enable the design of multiple implementation stages.

Finally, a detailed review of the redesigned network reveals instances where important local conditions were overlooked. Some bike paths may be suboptimally placed, on-street parking distribution fails to account for specific high-traffic businesses, and certain detours along one-way streets may appear arbitrary. This network design is not intended to provide a blueprint for direct implementation but rather to help explore how the transport system can function within the new paradigm. It provides a foundation for discussions on the future of urban transport systems. However, after adding local "overrides" (see the bottom row of Table 3.3), it can even help to guide the creation of an implementation plan.

6.3 Designs for streets and intersections

A tangible presentation of how our environments can look and feel is essential for discussing possible mobility futures. Le Corbusier's, Frank Lloyd Wright's, and Colin Buchanan's images of streets in a modern city maintain their normative power even almost a hundred years after their publication. They have steered the notion of a modern city and mobilized the intellectual efforts of planners to make (reduced versions of) them a reality.

Chapter 4 addresses how physical places in the E-Bike City will be designed while keeping the overarching transport network functional. It shows four well-known places in Zurich redesigned according to the concept introduced in Chapter 2. The design standards in Appendix A allow practitioners to extend the designs into other, similar cities.

The designs have multiple limitations. First, similar to the previous chapters, they are shown as overnight transitions without staging, and their locations are restricted to urban areas. Further work is needed to explore the possibilities of staging the implementation and what design elements are needed in places with lower density.

Second, the designs are restricted to the near future, striking a balance between the comfort and safety of cyclists on the one hand and minimizing the capital investments on the other. Changes in curbs are limited mostly to intersections, while the linear sections are implemented merely by changing the road paint. While these restrictions are valid for a quick transition in existing cities, further work will be able to inform the design in the long-term future or in rapidly growing cities where entire districts are being developed on green fields.

Third, the work in Chapter 3 has a strong transportation focus. Despite attempts to include aspects of urban design, the resulting designs still lack a comprehensive consideration of factors from other disciplines—notably architecture and history. Future versions of such designs must seek a balance between a functional transportation system and the qualities of space, material choice, and historical conservation.

Lastly, while the current work focuses on Zurich, future work is needed to localize the designs elsewhere.

6.4 Accessibility effects

Providing accessibility to people and businesses is the core mission of planners developing transportation systems. They can do so in a variety of ways. This thesis discusses the accessibility effects of the E-Bike City as an example of planning according to the "small infrastructure" paradigm. Understanding the effects includes the aggregate impacts but also their distribution among population groups. While the former allows conclusions about total gains or losses, the latter is essential for making judgments from the social equity perspective.

Chapter 5 has explored two research questions: (1) What are the effects of the E-Bike City in Zurich on mode choice and accessibility?; and (2) How would it impact different groups of people?

The redesigned network from Chapter 3 was inserted into an agent-based scenario in MATSim to simulate one full day of traffic with a synthetic population of roughly 2.6 million agents. Then, a personal logsum accessibility value was calculated for every individual in a randomly drawn sample, considering their residential location, sex, age, and driver's license ownership. The accessibility measure captures the ease of reaching destinations, considering travel times and the comfort of cycling as part of the total generalized costs. Thus, the reported effects capture simultaneously travel time losses felt by drivers due to congestion and the safety and comfort benefits of separated infrastructure experienced by cyclists. A discrete choice model from previous work conducted in Zurich allows the conversion of utilities between these seemingly incommensurable effects.

The mode shares shift in favor of cycling and public transport. The car kilometers traveled across the entire region decreased by 3% and roughly 51'000 of today's drivers switch entirely to other modes. On trips within the city, total car kilometers traveled decreased by 10.2%. Local streets in neighborhoods and on-street parking experienced an even more substantial decline in car traffic due to 29.7% fewer car trips within the city and roughly 30'000 people not using their cars anymore. On the other hand, distance traveled on public transport has increased by 9.5% across the entire region and by 28.2% on trips within the city. The distance traveled on bicycles and e-bikes increased by 7-15% across the entire region and roughly 40-50% on trips within the city. However, besides mode shifts, the total distance traveled grew as well. The number of passenger kilometers in public transport, cycling, and walking increased roughly 150% more compared to the decrease in car travel.

The changes in accessibility lower the disparities between the highest and the lowest accessibility levels. This happens mainly through a redistribution of accessibility between drivers and non-drivers (with or without a driver's license). Declining car accessibility and growing cycling accessibility compensate each other to some extent, leading to less extreme overall changes than considering individual modes. However, considering all modes across the whole region, the median accessibility change is negative, indicating an accessibility decline.

Shifting to the "small infrastructure" paradigm offers substantial opportunities for the city and the entire region to promote a mode shift to sustainable modes and make the distribution of accessibility more equitable. However, the results also indicate three caveats that need further attention. First, the overall accessibility decreases. Second, the total distance traveled increases, implying that the altered transport system needs to provide a higher overall capacity than today. Third, the reduced capacity of main roads in the city increases traffic through the neighborhoods.

Nevertheless, the results and the caveats are subject to multiple methodological limitations. The impacts are measured under the assumption of today's behavior and long-term decisions like land use and mobility tool ownership. The mode choice model used is a recent work, still subject to discussions and improvements, and the benefits of cycling infrastructure are still considered in a rather rudimentary way. Moreover, the network design is based on heuristics that made it possible to produce realistic networks while still allowing enough time for the remaining steps of this dissertation. More accurate, optimization-based approaches may yield better accessibility levels. Lastly, the scenario considered has only focused on the road space reallocation and did not include other policy measures that would typically complement such transformations.

Future work on the impact assessment should aim for a better understanding of the effects, especially with long-term changes in demography, mobility tool ownership, land use, and behavior. Further advancement of the design techniques (see Section 6.2) should enable more optimal combinations of cycling and car accessibility or even a design process driven by the resulting accessibility structures rather than functional elements like detours and travel times (e.g., building on ideas in Martens (2016)). Finally, complementing the E-Bike City with further policy measures like road pricing or changes in public transport will enable a more holistic understanding of the future potentials.

6.5 Future work directions

The thesis has answered its overarching question by providing a tangible design of the E-Bike City in Zurich. It also provided a framework for repeating this design exercise with different assumptions and elsewhere in the world. However, multiple aspects have been omitted and must be addressed in future work.

First, methodological limitations of network design and impact assessment restrict the level of detail at which proposals and conclusions can be made. Some of these shortcomings are due to a lack of empirical evidence, and others are due to simplifications necessary to complete this work on time. Future work should advance the impact assessment methodology to deepen our understanding of disruptive transport policies like the E-Bike City,

Second, the designs provided in this work focus only on the city and do not consider ways of transforming the transportation systems in suburban regions. Advancing the concept further into such spatial contexts is another important issue to be addressed in future work.

Lastly, the concept has focused on transportation in Zurich while neglecting the effects on urban design, the wider cultural significance of cycling, and possible concepts that could be applied in other cities and cultures. Reconciling the need for sustainability and accessibility with urban design and cultural expectations and expanding the concept into other places are further important avenues of future work.

6.6 Reflections

This thesis was subject to multiple challenges, both regular ones faced by many other researchers, as well as those that are rather unusual in academic research. First, it had to propose an evidence-driven alternative design for real built environments, balancing high-level scientific rigor and many practicalities to be considered. Academic studies can typically isolate a partial concept or aspect while not attempting to provide answers in other areas. For example, Szell *et al.* (2022) and Steinacker *et al.* (2022) propose ways to generate optimal cycling networks without considering the limited road space. Representing the results in abstract maps or charts does not force a reconciliation with all practical details of everyday life, such as where these proposed cycling paths would be built. On the other hand, practitioners focus on puzzle-solving these details without changing the high-level concepts. This work had to manage both aspects simultaneously, using high-levels analytics to change the basic assumptions while at the same time present the resulting designs of the network as well as well-known places that are subject to practical scrutiny by people who use them every day.

The second challenge lies in combining quantitative research, qualitative design work, and leadership. Parts of this thesis required months of focused literature research, programming, and data interpretation. Other parts required creative sketching and design concepts, contrary to the deep focus needed for software development. Simultaneously, it was necessary to ensure a consistent direction among the wider team of researchers, external suppliers, students, and temporary employees. Admittedly, a careful examination of the four chapters will reveal some inconsistencies that stem from the complex task of coordinating these aspects simultaneously.

Overall, writing this thesis during the last three and half years was an iterative process, with many learnings and shifts in the underlying assumptions along the way. Kuhn (1962) argues that textbooks make scientific revolutions invisible by presenting only the most recent state of knowledge. The same applies to this thesis that makes the many turns and previous working directions invisible. Numerous versions of previous designs, many created by students, have not found their way into the final version. Yet, they served as valuable proofs of concept, helping to develop the final designs. Also, much time was spent developing and adjusting the methodological tools, such as formulating the concept, developing the network generation software, and building the agent-based simulation. Now that these foundational tools and experiences are in place, future researchers have an excellent foundation for designing the future at a much faster pace and with a stronger focus on results rather than the process.

Chapter A: Appendix: Design Manual

This chapter has been created jointly with Matias Cardoso. The individual contribution of Lukas Ballo consisted of the conceptualization of the design scenarios and writing the manuscript. Matias Cardoso has designed and drafted the standard solutions. The concept of this chapter is inspired by his background research documented in Chapter 4.

A.1 Introduction

Municipal planning authorities seeking to implement the principles of the E-Bike City can refer to this manual for standardized design guidelines. Its structure is aligned with norms issued by the Swiss Association of Road and Transport Officials, *Verband der Strassen- und Verkehrsfachleute* (VSS).

A.2 Purpose

This manual facilitates the transition from existing urban street designs to those in an E-Bike City. The concept was developed as a strategy to address urban mobility challenges by restructuring transport systems around sustainable travel modes (Ballo *et al.*, 2023, 2024).

A.3 Scope

This manual provides complete design specifications for typical streets and intersections in Swiss cities (based on Zurich), following the principles of the E-Bike City concept. It is inspired by elements in the existing design standards and guidelines (ASTRA, 2022; Kanton Zürich, 2023; Stadt Zürich, 2024; NACTO, 2025; CROW, 2016) and demonstrates how they can be integrated to create a cohesive and functional cycling network.

A.4 Usage

This design manual provides guidance for the physical implementations of the network design for an E-Bike City introduced in Chapter 3. Tables A.1 and A.2 show overviews of the standard design solutions provided for different types of streets and intersections.

Table A.1: Overview of standard design solutions for streets

Type	Function	Dir.	Tram	Parking	Status quo	Archetypes: Separated one-way cycling paths	Archetypes: Separated two-way cycling paths	Archetypes: Cycling street
R1	Residential Str.	→	No	Yes	R1-Base	R1-A2, R1-A3	R1-A4	R1-A1
R2	Residential Str.	↔	No	No	R2-Base	-	-	R2-A1
R3	Residential Str.	→	No	Yes	R3-Base	R3-A2	-	R3-A1
S1	Secondary Str.	↔	No	No	S1-Base	S1-A1	S1-A3	S1-A2
S2	Secondary Str.	↔	Yes	No	S2-Base	S2-A2*	S2-A1	-
P1	Primary Str.	↔	Yes	No	P1-Base	P1-A1	P1-A2	-
P2	Primary Str.	↔	No	No	P2-Base	P2-A1,P2-A2,P2-A4	P2-A3	-

* With partially removing the separation of public transport

Table A.2: Overview of standard design solutions for intersections

Minor Street	Major street: R1-Base	R1-A3	S2-Base	S2-A1	S2-A2	P1-Base	P1-A1	P1-A2
R1-Base	RR-Base	-	-	-	-	PR-Base	-	-
R1-A1	-	RR-A1	-	-	-	-	-	PR-A1
R1-A4	-	-	-	-	-	-	PR-A2	-
R3-Base	-	-	SR-Base	-	-	-	-	-
R3-A1	-	-	-	SR-A3	SR-A1,SR-A2	-	-	-
S1-Base	-	-	-	-	-	PS-Base	-	-
S1-A1	-	-	-	-	-	-	PS-A2	PS-A1

A.5 Parking

Under conditions of limited road space, prioritizing cycling and other small-scale modes of transport necessitates a substantial reorganization of on-street motor vehicle parking. However, access to buildings must remain guaranteed through the provision of short-term parking spaces within walking distance from all destinations. The process for allocating parking is detailed in Chapter 3.

On-street parking for motor vehicles will be typically concentrated on some streets, where a portion of the roadway width will be allocated for parking spots. Other streets will be kept free of on-street parking, allowing an uninterrupted cycling infrastructure.

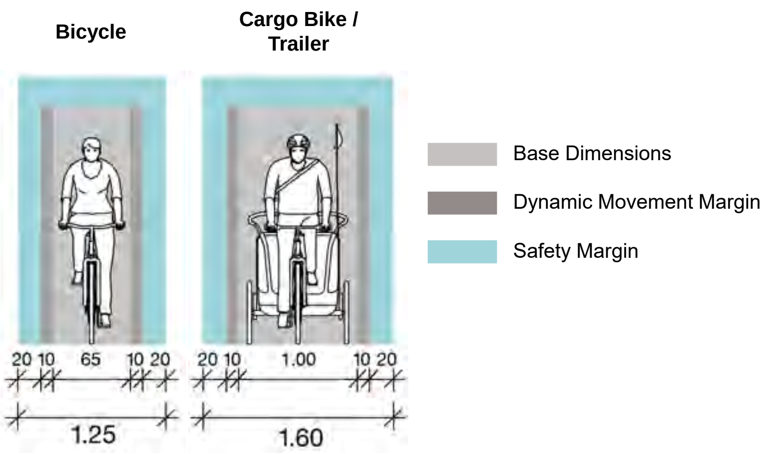
In contrast, bicycle parking will be distributed in small clusters along all streets to provide easy access. These facilities will be located along building facades or as part of a physical separation between different transportation modes. Large bicycle parking hubs at major activity centers require separate site-specific planning and are not covered in this design guide.

A.6 Dimensions

The recommended widths of cycling infrastructure elements are based on clearance profiles in the **VSS 40201** norm VSS (2019), illustrated in FigureA.1. They consist of three components: (1) Base dimensions, (2) Dynamic movement margin, and (3) Safety margin. In the case of cyclists riding side by side, the safety margin between them is applied only once. For motorized vehicles, a unified width of 3 meters is assumed which is sufficient for cars, delivery vans, and light trucks.

Each dimension is defined in two levels: minimum and desirable. The minimum dimensions require that all cycling facilities are sufficient for one cargo bike/trailer per direction. The

Figure A.1: Clearance profiles of cyclists



Adapted from Kanton Zürich (2023).

desirable case, however, requires enough space for two cyclists riding side by side ("social cycling") and safe overtaking, resulting in three cyclists for a single direction and five in the case of two-way paths.

A.7 Standard designs for streets

This section shows standard design solutions for combinations of street type and design archetype. The dimensions are based on typical situations in Zurich and are in meters. For general recommendations on minimal and desired dimensions, please refer to table A.3.

Table A.3: Minimum and desirable widths

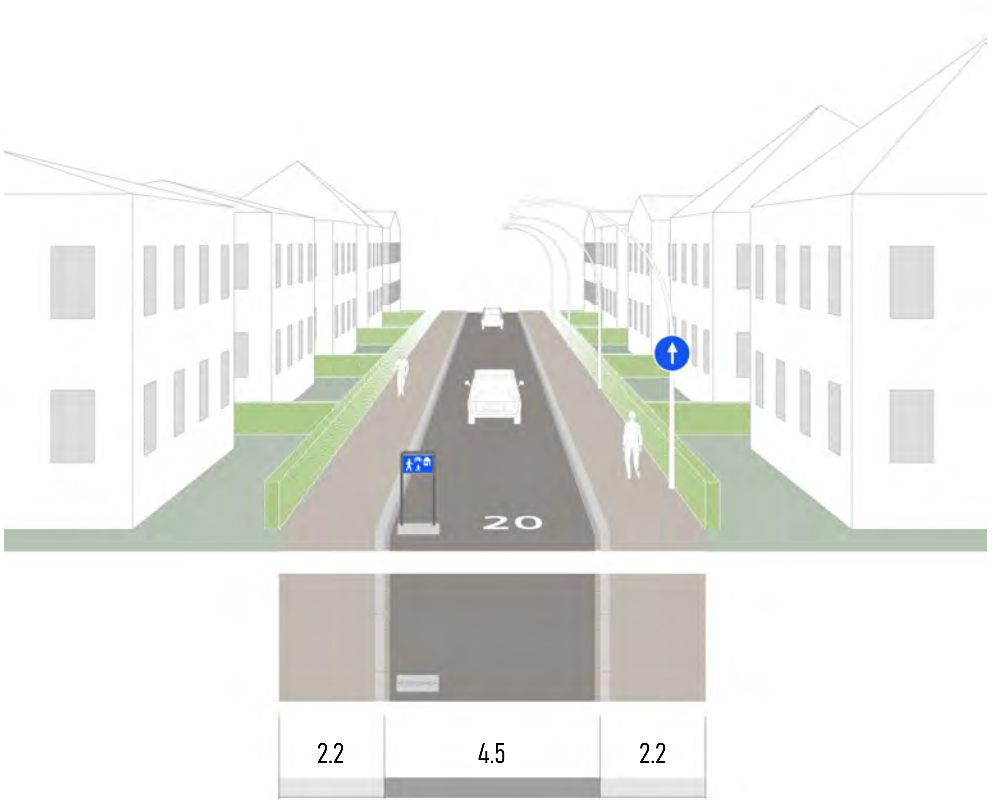
Archetype	Minimum		Desirable	
	Width	Passing scenario*	Width	Passing scenario*
One-way cycling lanes/paths	1.6m	C	4.25m	CB ¦ C
Two-way cycling paths	3.2m	C | C	7.1m	CB ¦ C | CB
Cycling streets	4.6m	C | M	5.65-6.5m†	CB | M

*B: Bicycle (1.25m), C: Cargo bike/trailer (1.6m), M: Motorized vehicle - delivery van (3.0m), ¦: Overtaking, |: Opposite directions

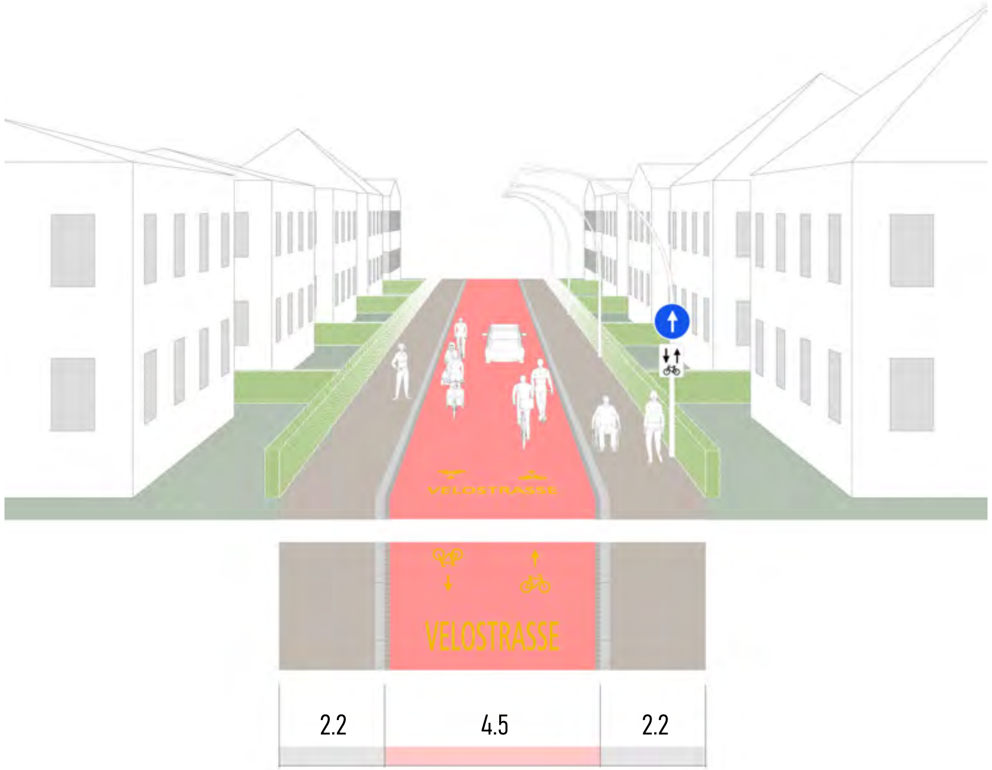
† Maximum width to avoid high speeds of motorized traffic

A.7.1 R2: Residential street, two-way, without parking

A.7.1.1 R2-Base: Mixed traffic (status quo)

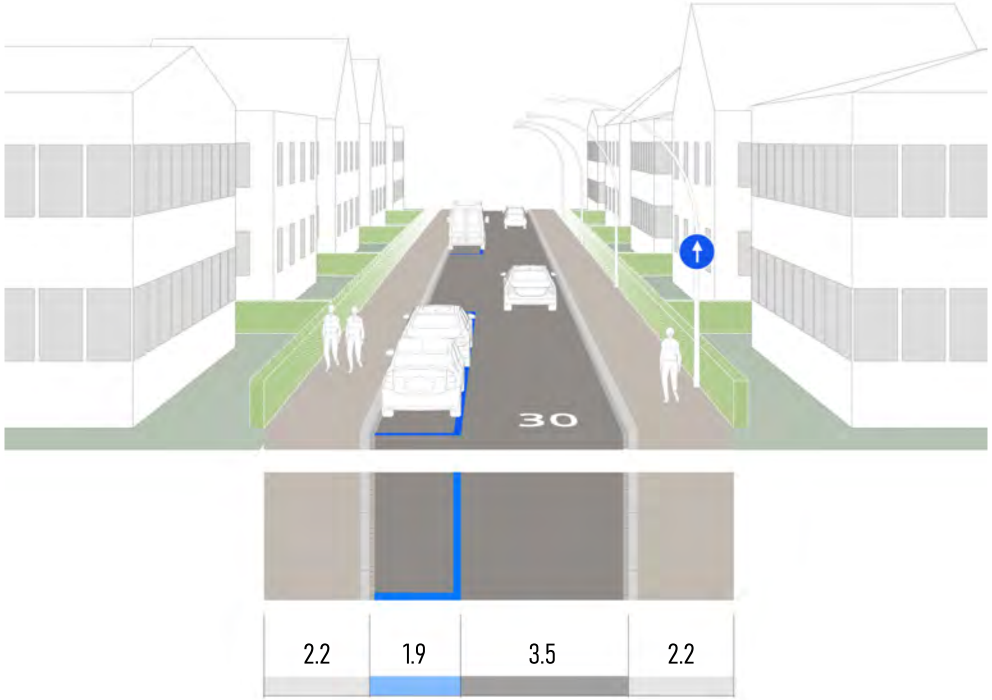


A.7.1.2 R2-A1: Cycling street

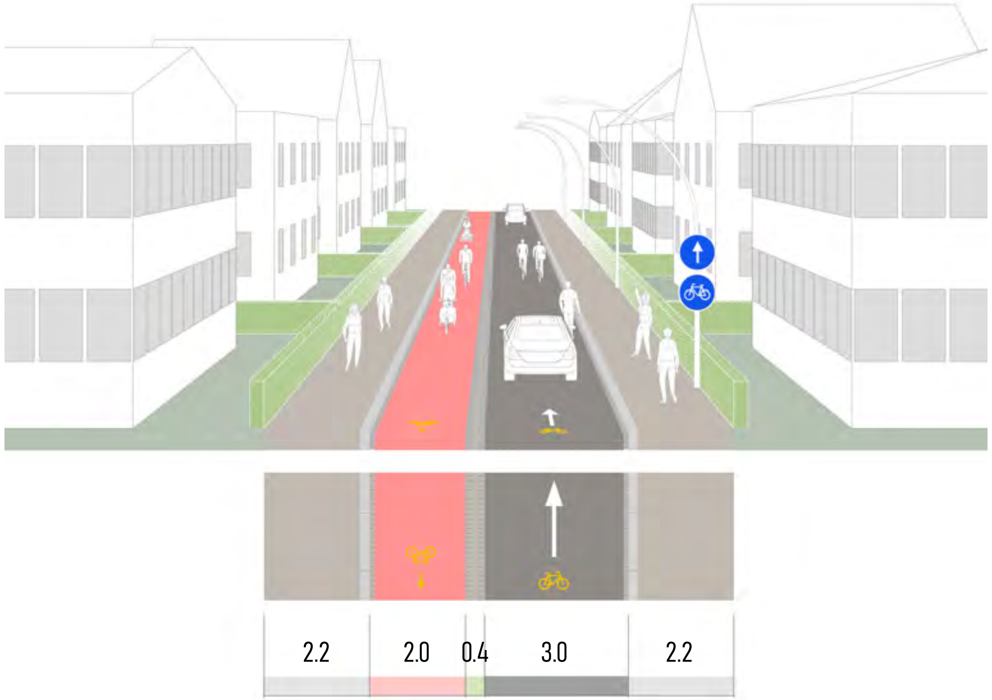


A.7.2 R3: Residential street, one way, with parking

A.7.2.1 R3-Base: One-way mixed traffic with parking (status quo)



A.7.2.2 R3-A2: One-way mixed traffic, with separated contraflow cycling path



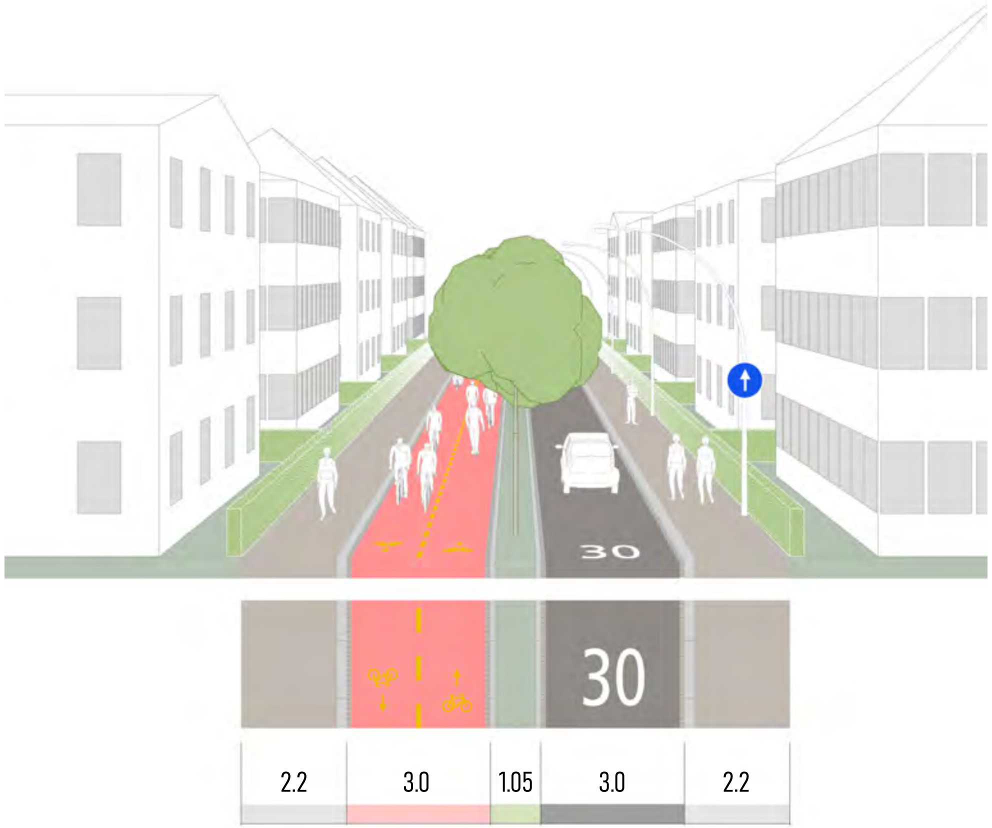
A.7.2.3 R3-A1: Cycling street

A.7.3 R1: Residential street, two ways, with parking

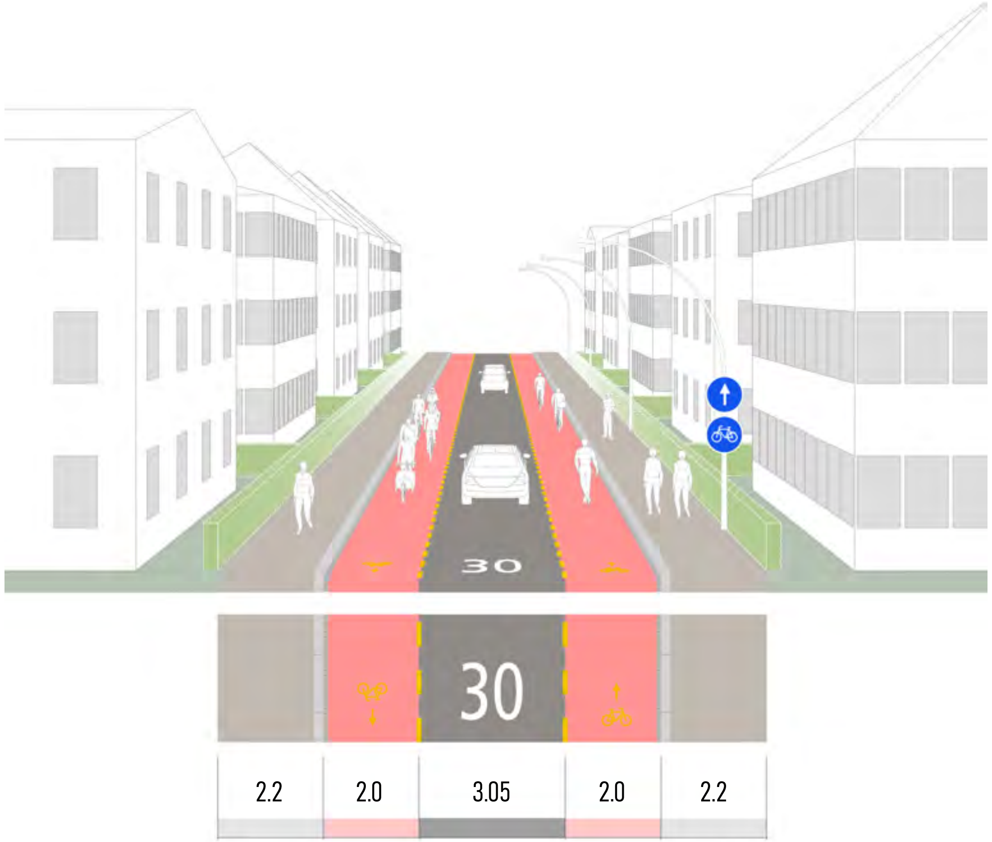
A.7.3.1 R1-Base: Two-way mixed traffic, with parking (status quo)

A.7.3.2 R1-A3: One-way mixed traffic with parking and separated contraflow cycling path

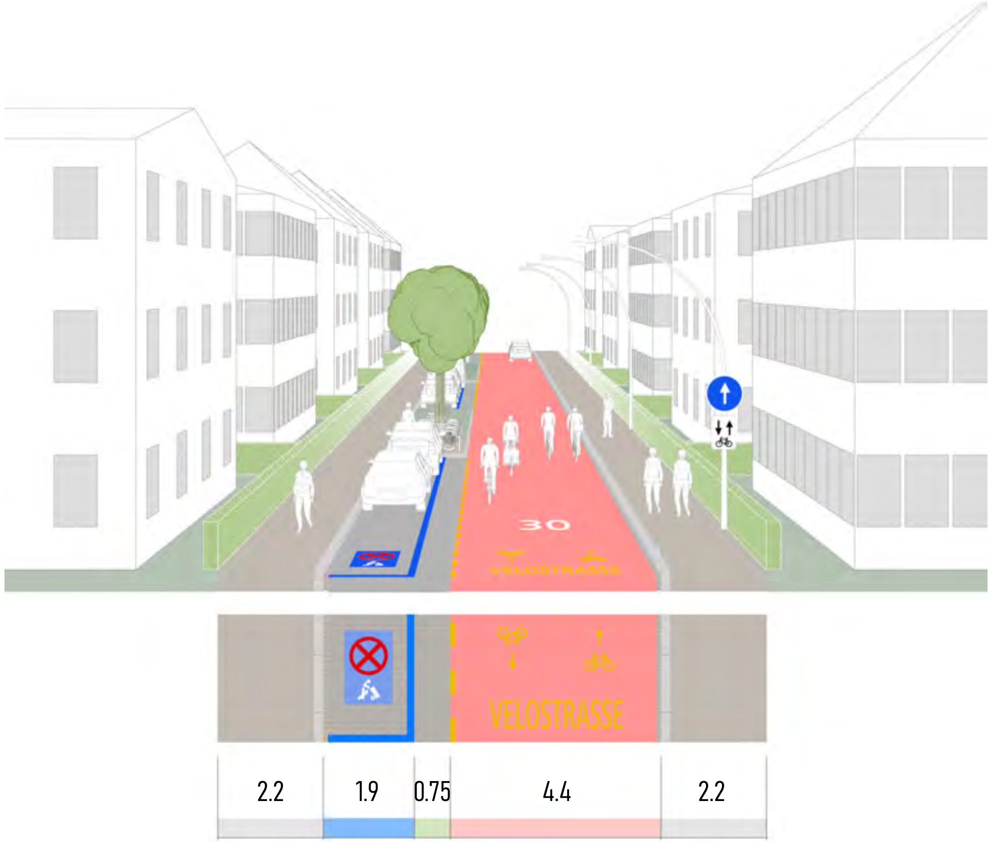
A.7.3.3 R1-A4: One-way motorized traffic and separated cycling path



A.7.3.4 R1-A2: One-way motorized traffic, with cycling lanes

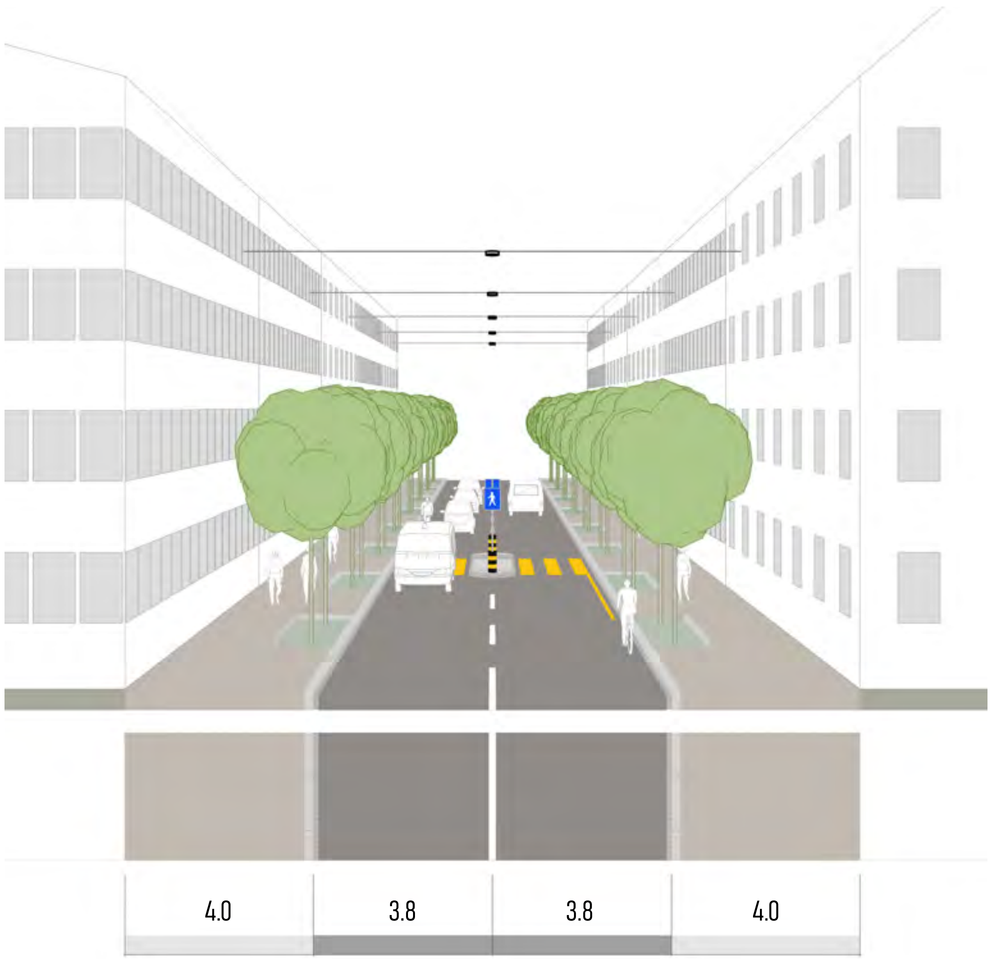


A.7.3.5 R1-A1: Cycling street

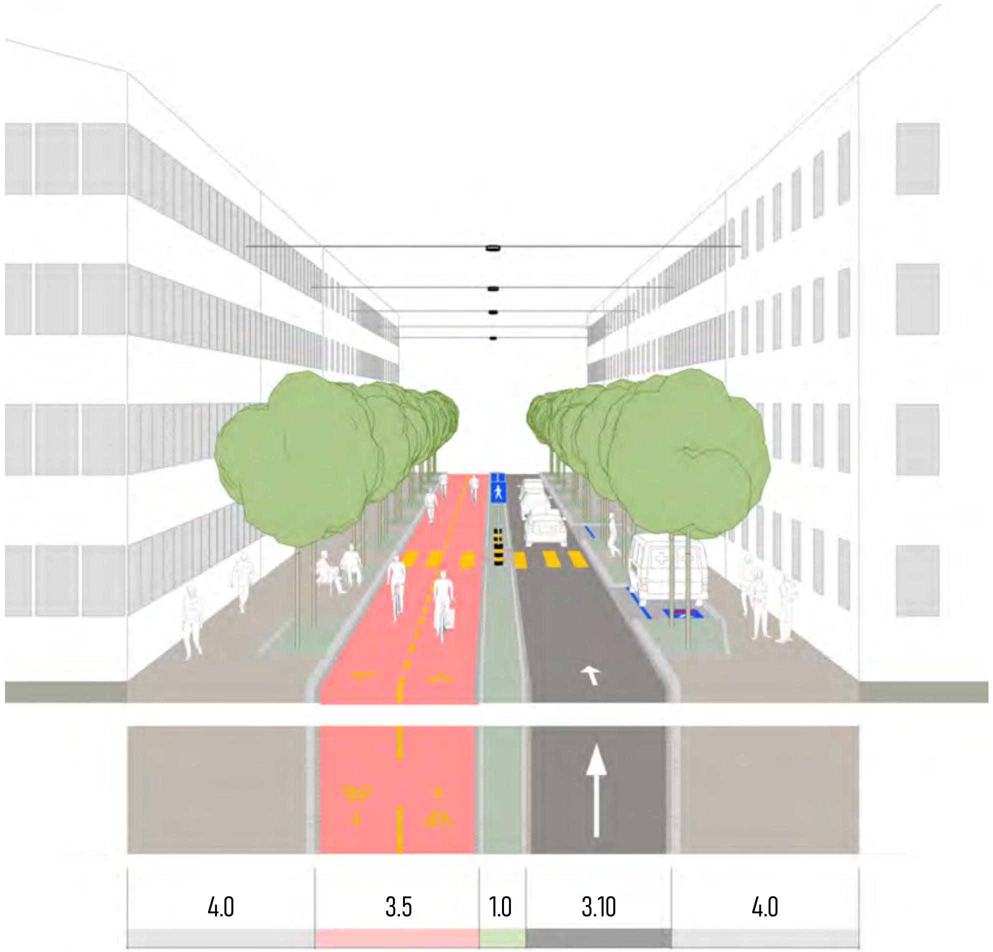


A.7.4 S1: Secondary street, without tram

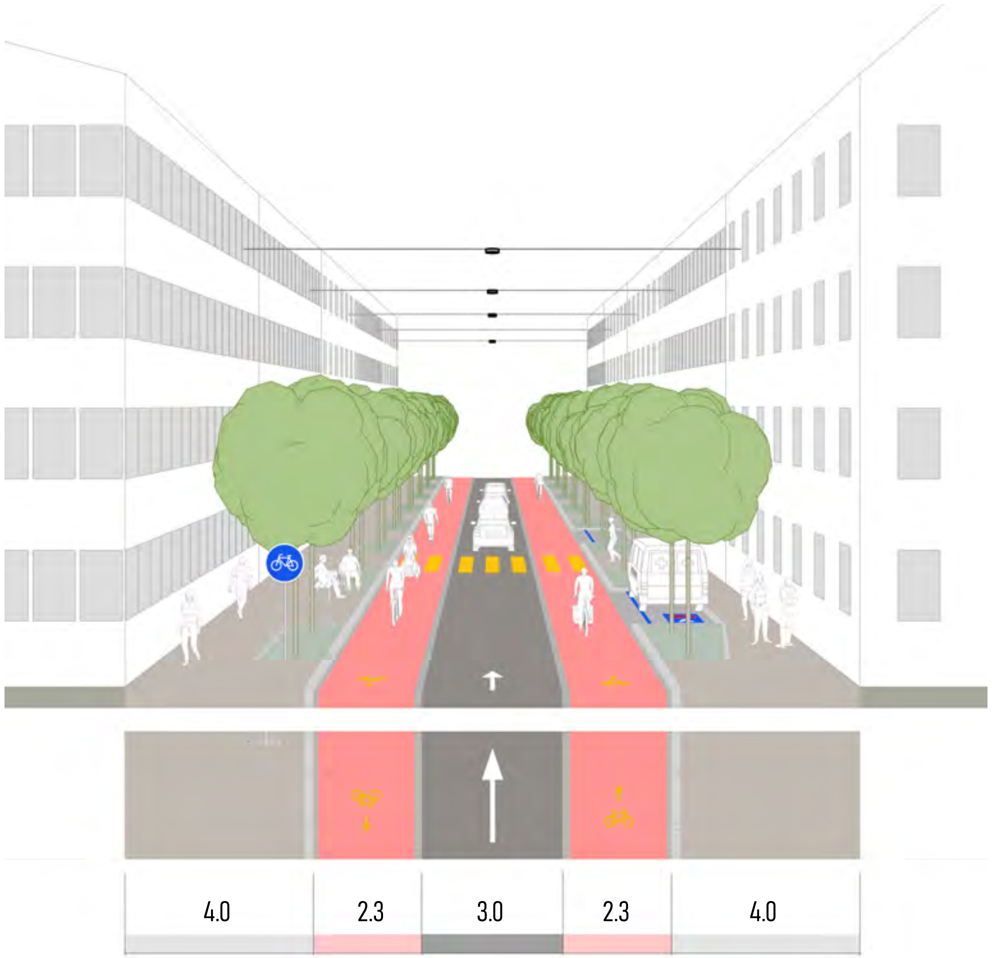
A.7.4.1 S1-Base: Two-way motorized traffic with advisory cycling lanes (status quo)



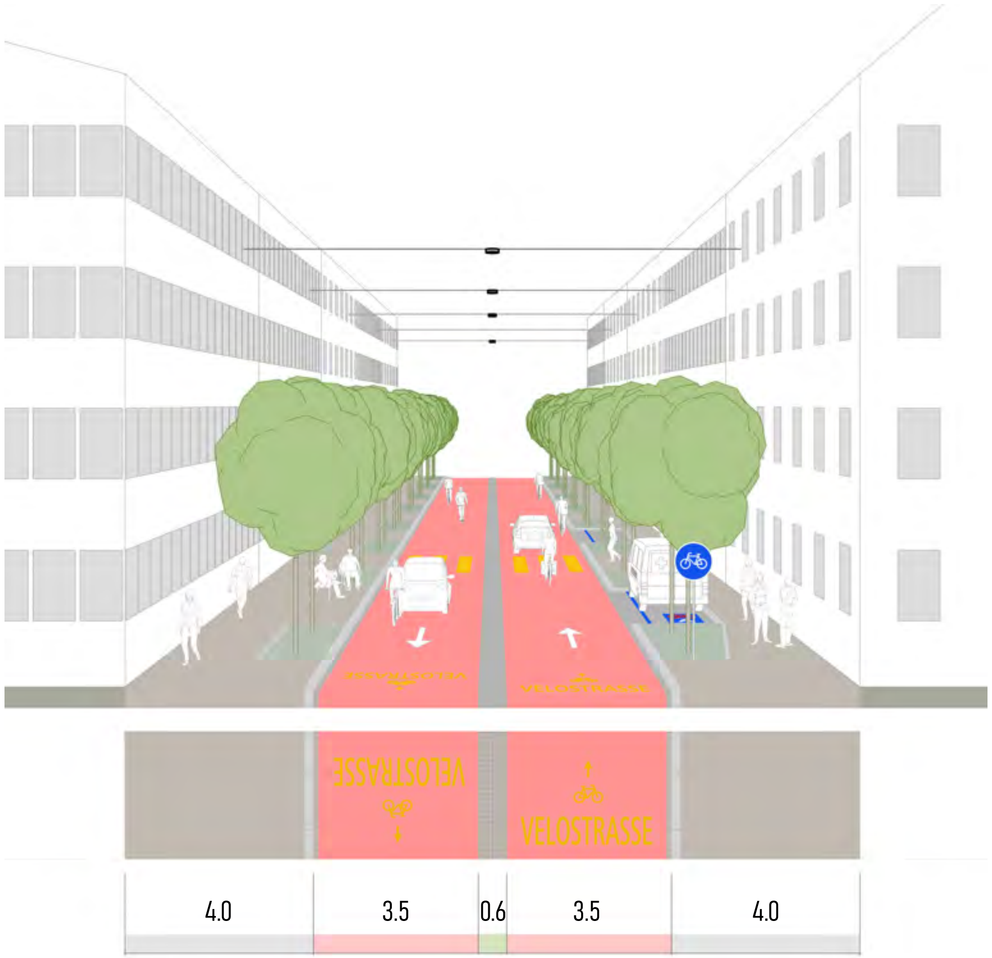
A.7.4.2 S1-A3: One-way motorized traffic, with separated cycling path



A.7.4.3 S1-A1: One-way motorized traffic, with separated cycling paths

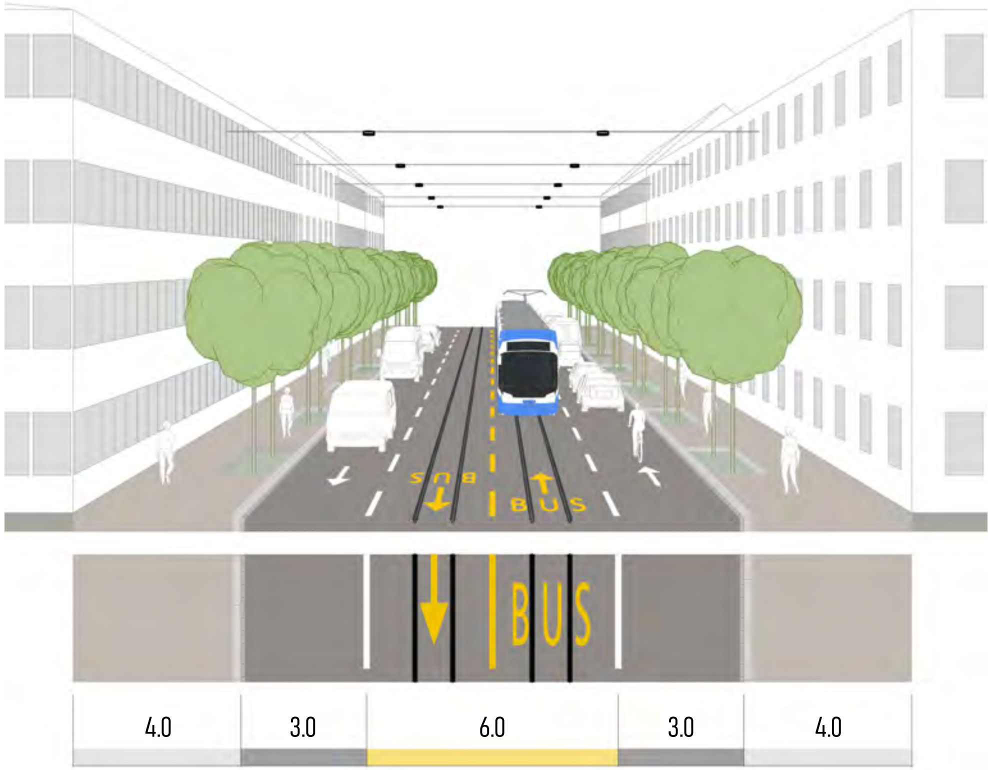


A.7.4.4 S1-A2: Cycling street

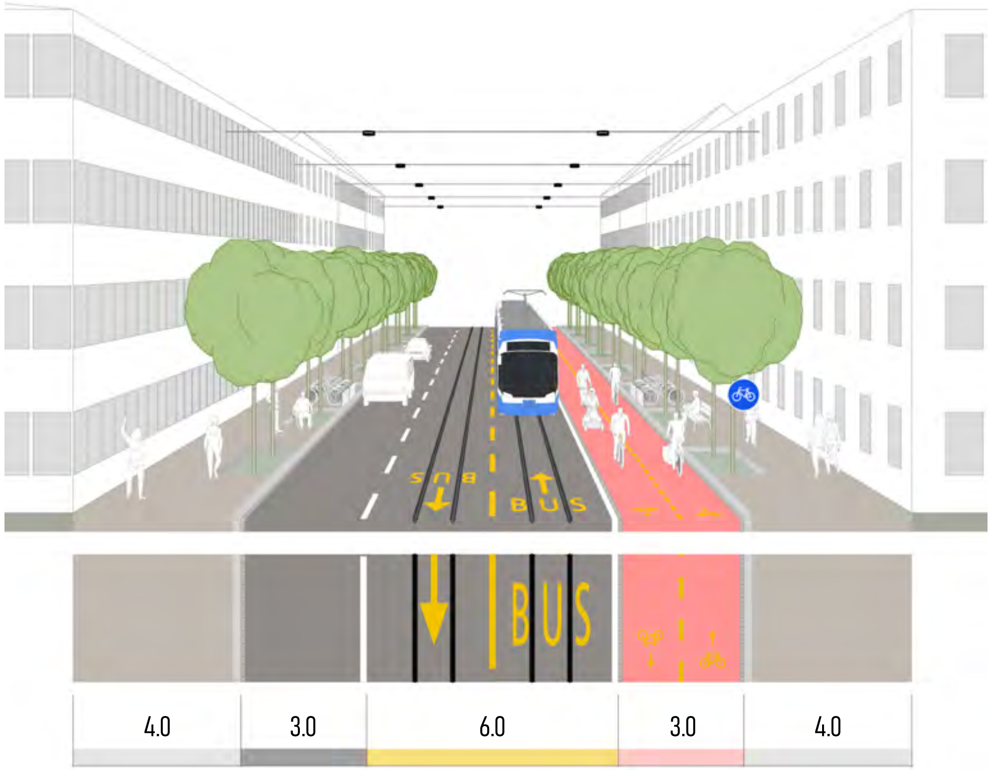


A.7.5 S2: Secondary street, with tram

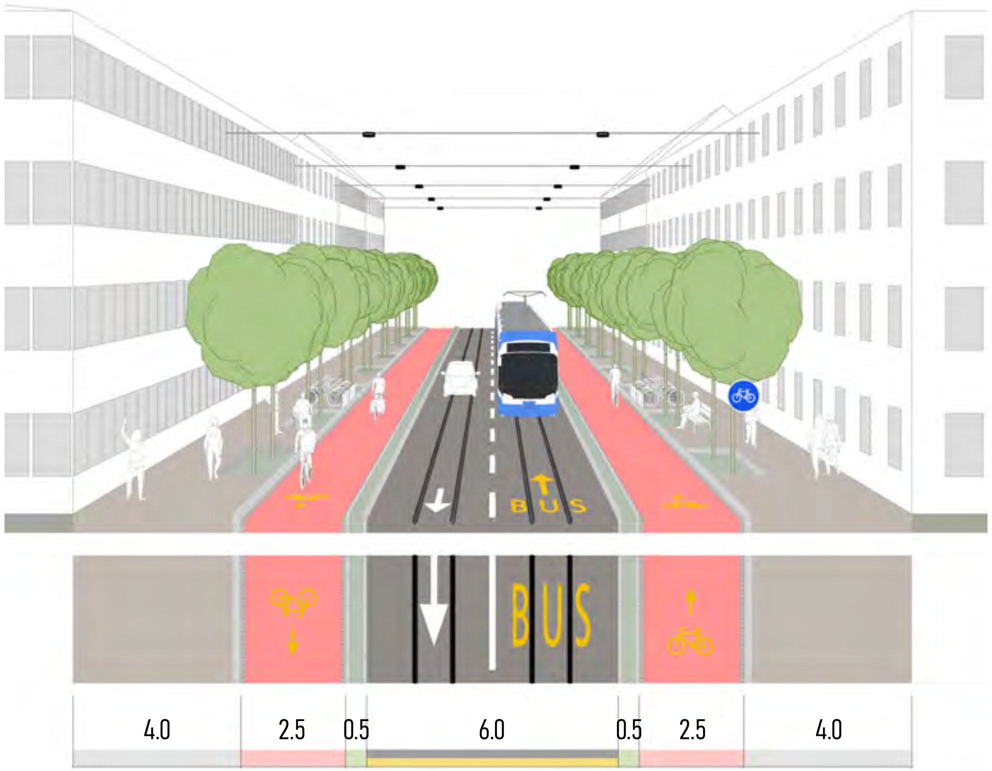
A.7.5.1 S2-Base: Two-way mixed traffic, with center-running bus/tram lanes (status quo)



A.7.5.2 S2-A1: One-way motorized traffic, with center-running bus/-tram lanes, and minimalistic cycling path

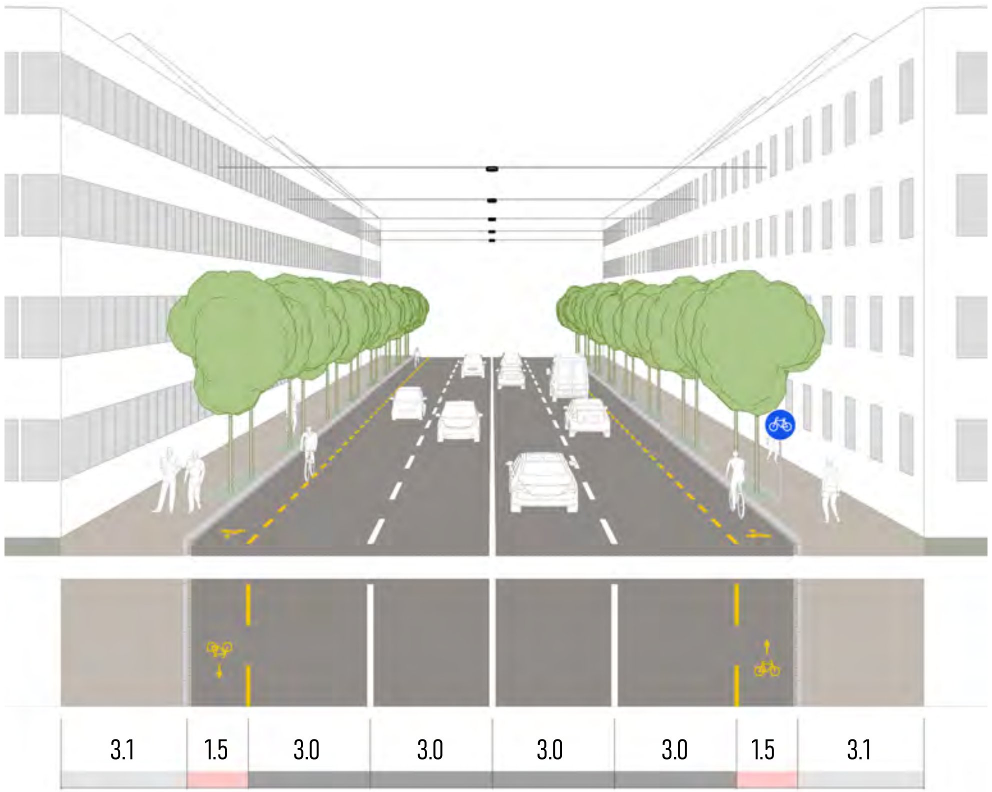


A.7.5.3 S1-A2: One-way motorized traffic, with contraflow bus/tram lane and high-comfort cycling paths

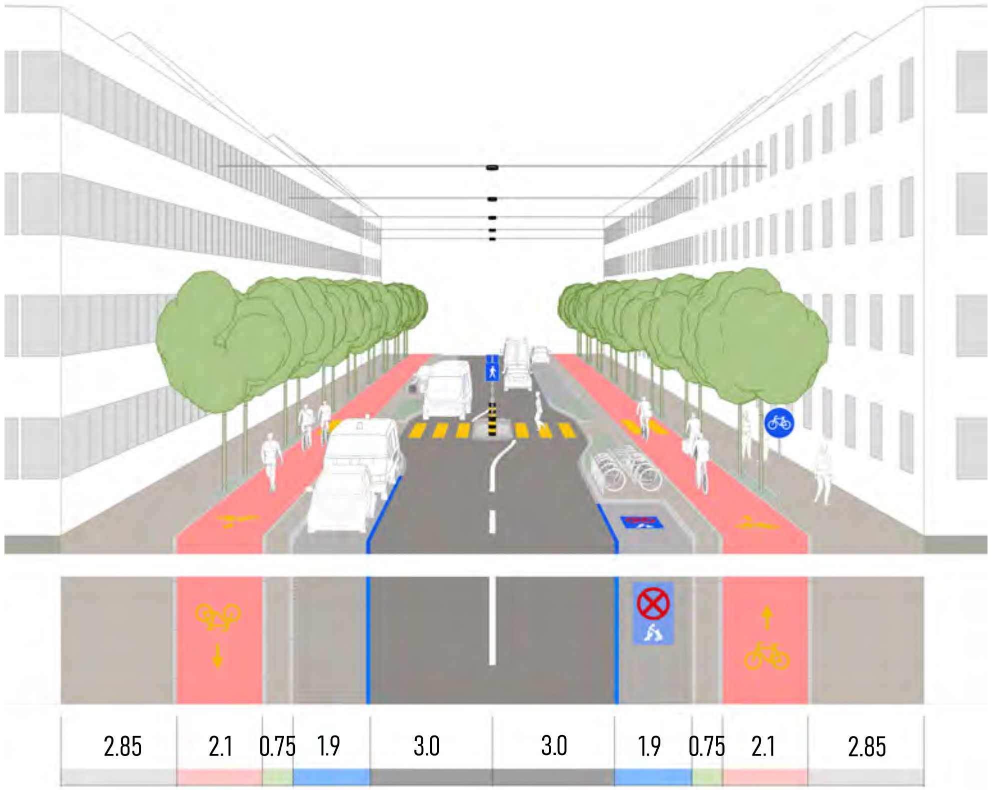


A.7.6 P2: Primary street, without tram

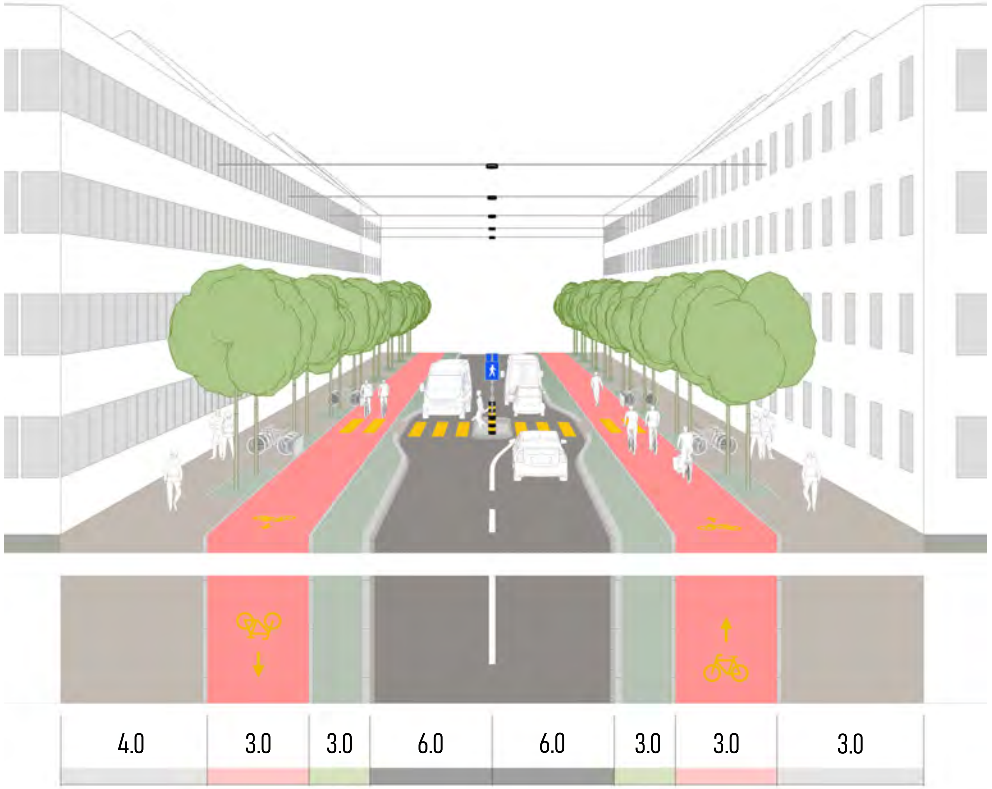
A.7.6.1 P2-Base: Two-way motorized traffic, with double lanes and advisory cycling lanes



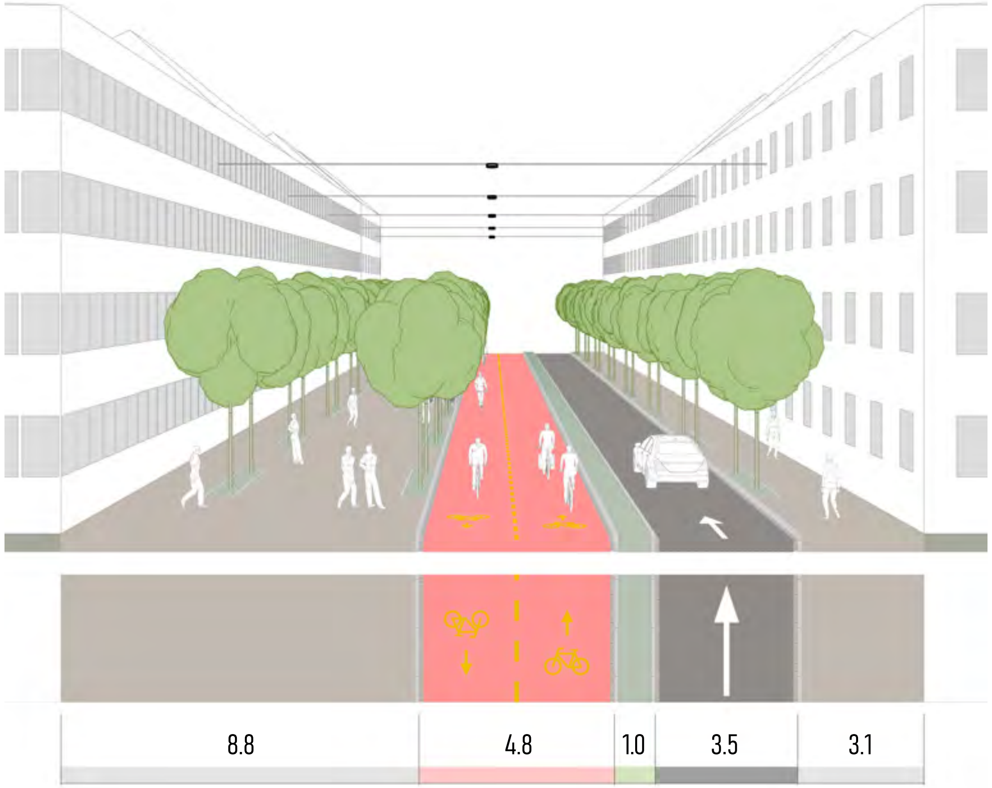
A.7.6.2 P2-A2: Two-way motorized traffic, with separated cycling paths and parking



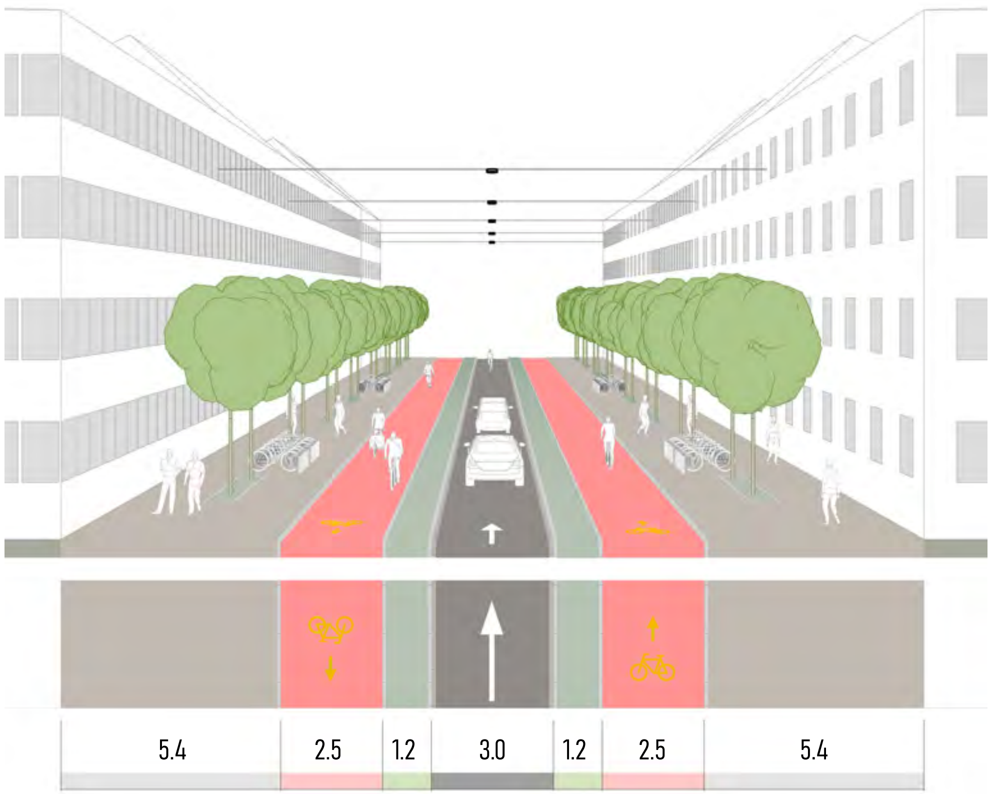
A.7.6.3 P2-A1: Two-way motorized traffic, with separated cycling paths



A.7.6.4 P2-A3: One-way motorized traffic, with very high-comfort separated cycling path

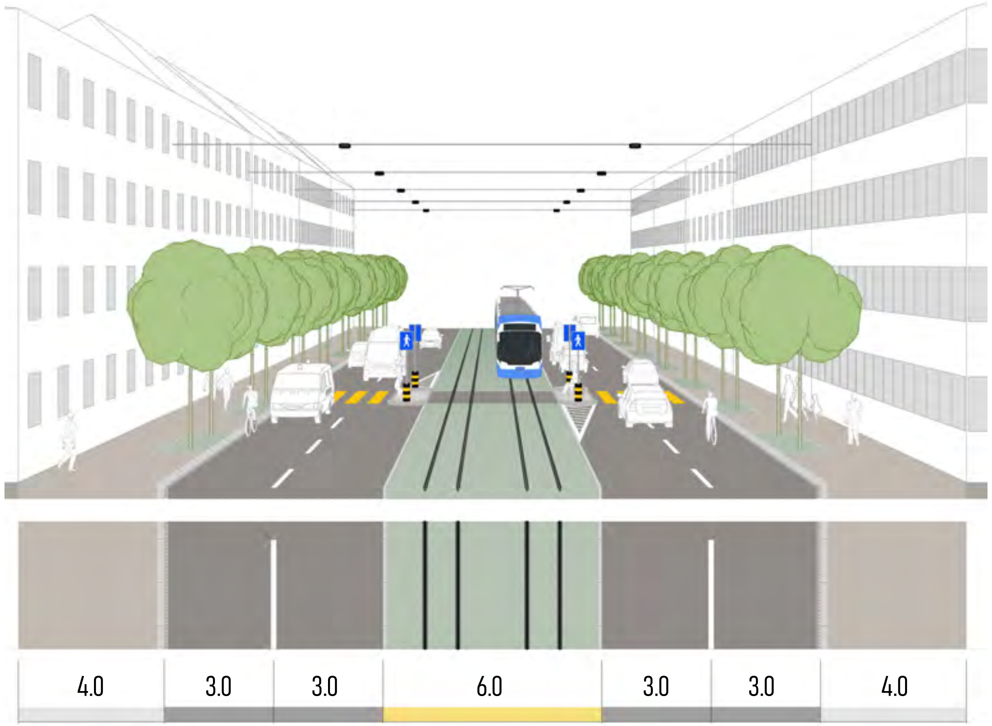


A.7.6.5 P2-A4: One-way motorized traffic, with very high-comfort separated cycling paths

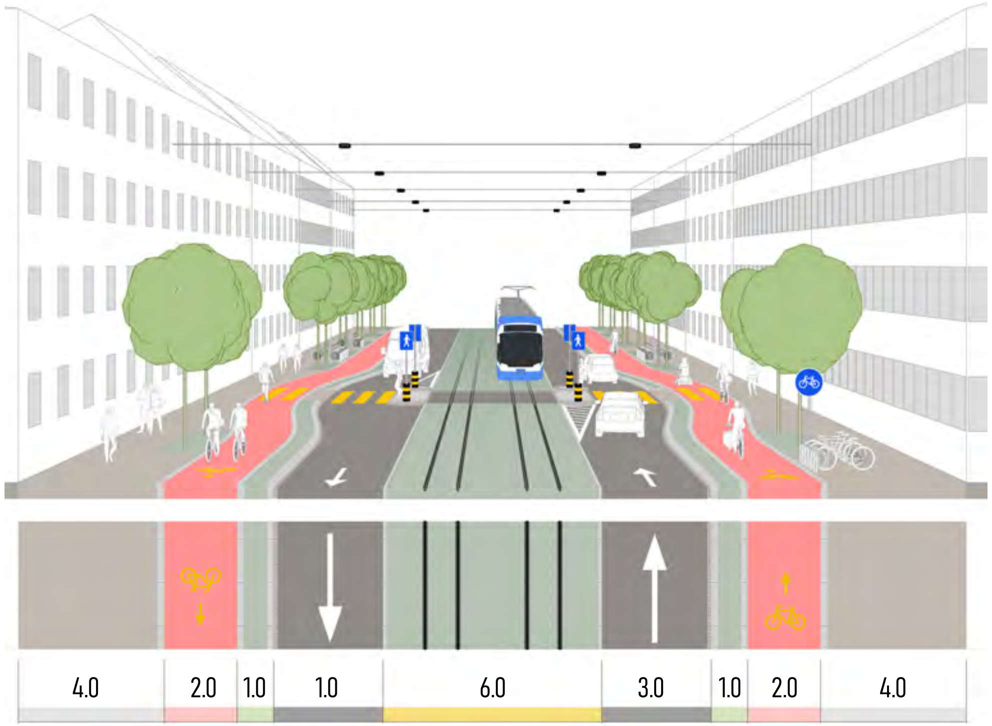


A.7.7 P1: Primary street, with tram

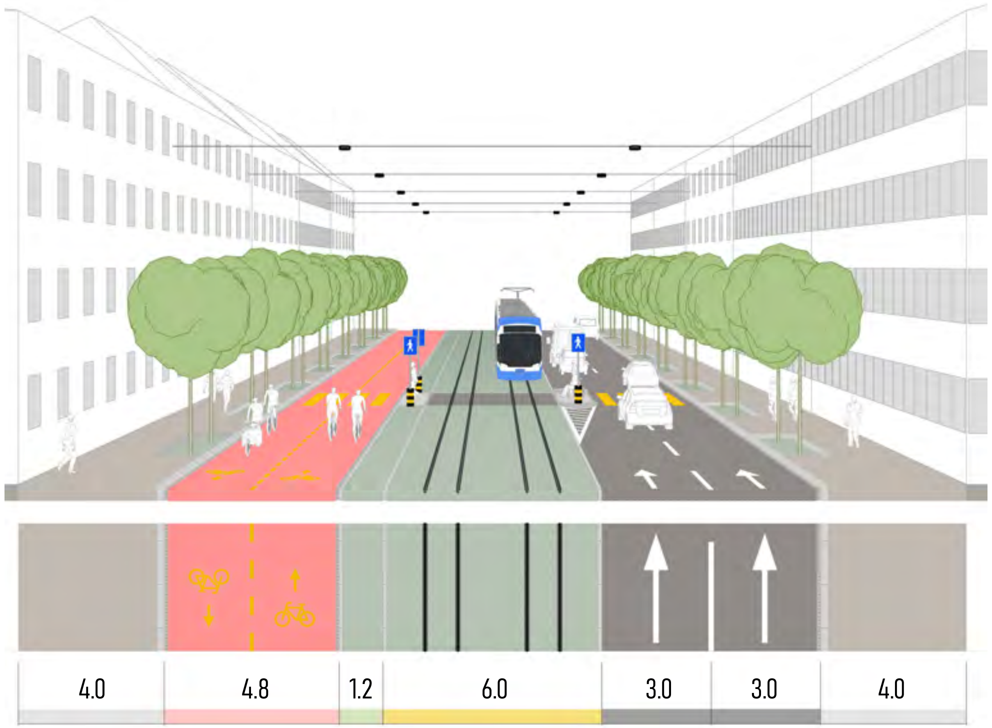
A.7.7.1 P1-Base: Two-way mixed traffic, with double lanes and center-running bus/tram lanes (status quo)



A.7.7.2 P1-A1: Two-way motorized traffic, with center-running bus/-tram lanes, and separated cycling paths



A.7.7.3 P1-A2: One-way motorized traffic, with center-running bus/-tram lanes, and separated cycling path

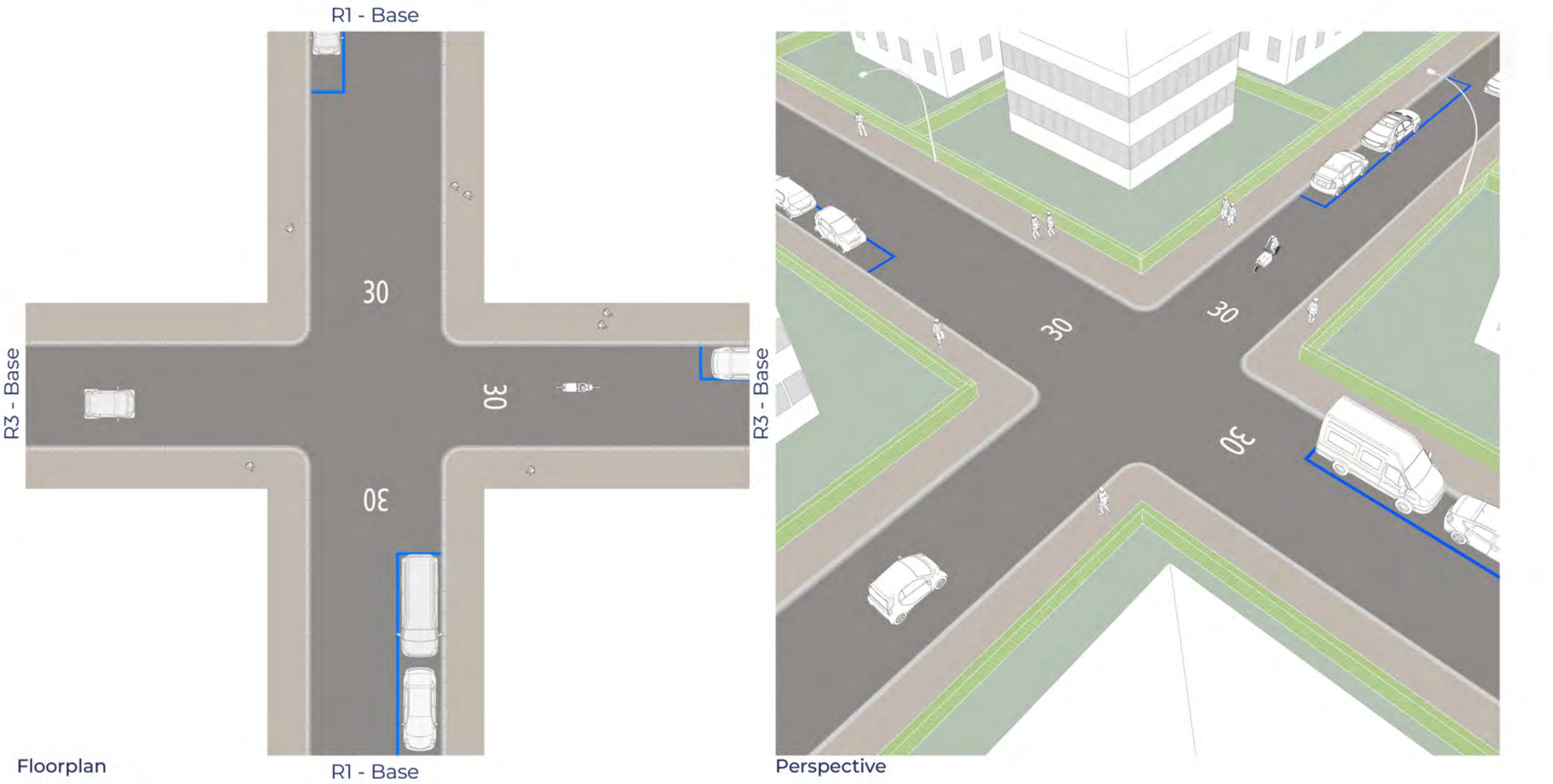


A.8 Standard designs for intersections

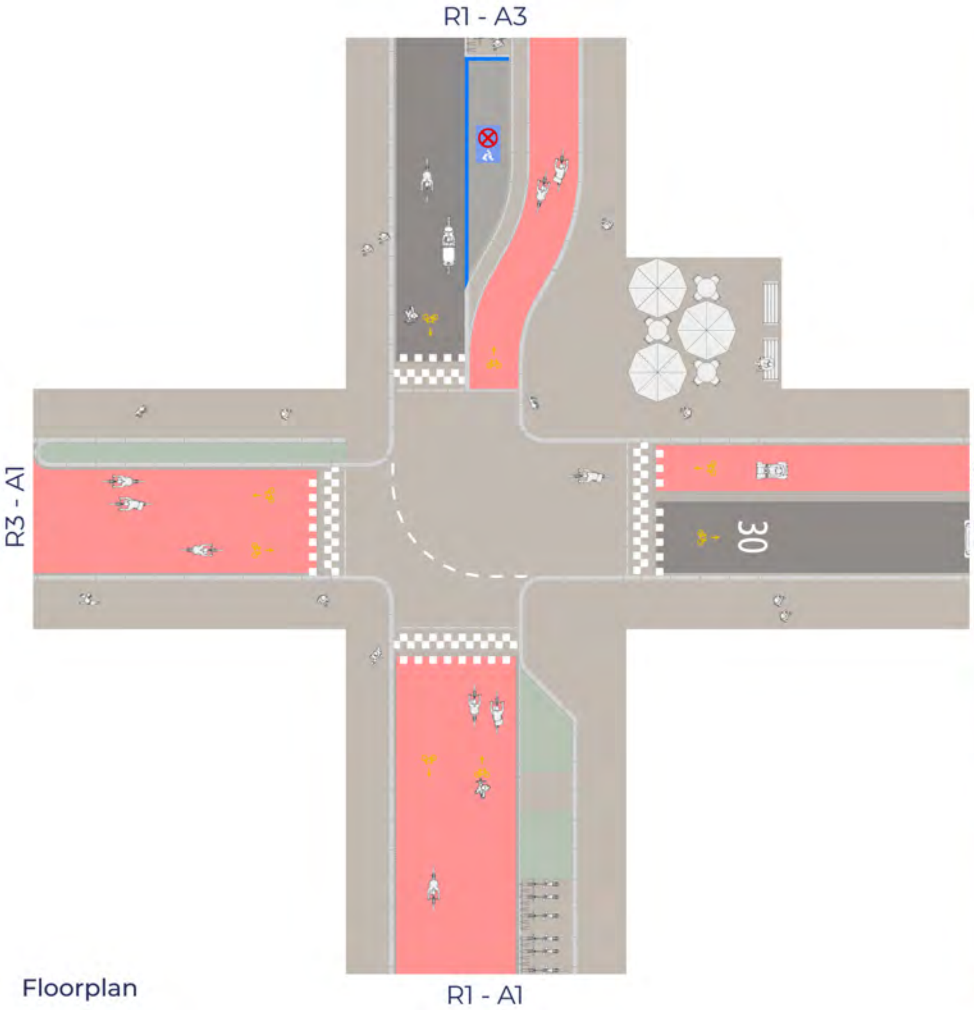
This section provides standard designs for intersections with combinations of street designs in Section A.7. The individual arms are labeled with their respective street types. Refer to the previous section for the typical dimensions.

A.8.1 RR: Two residential streets

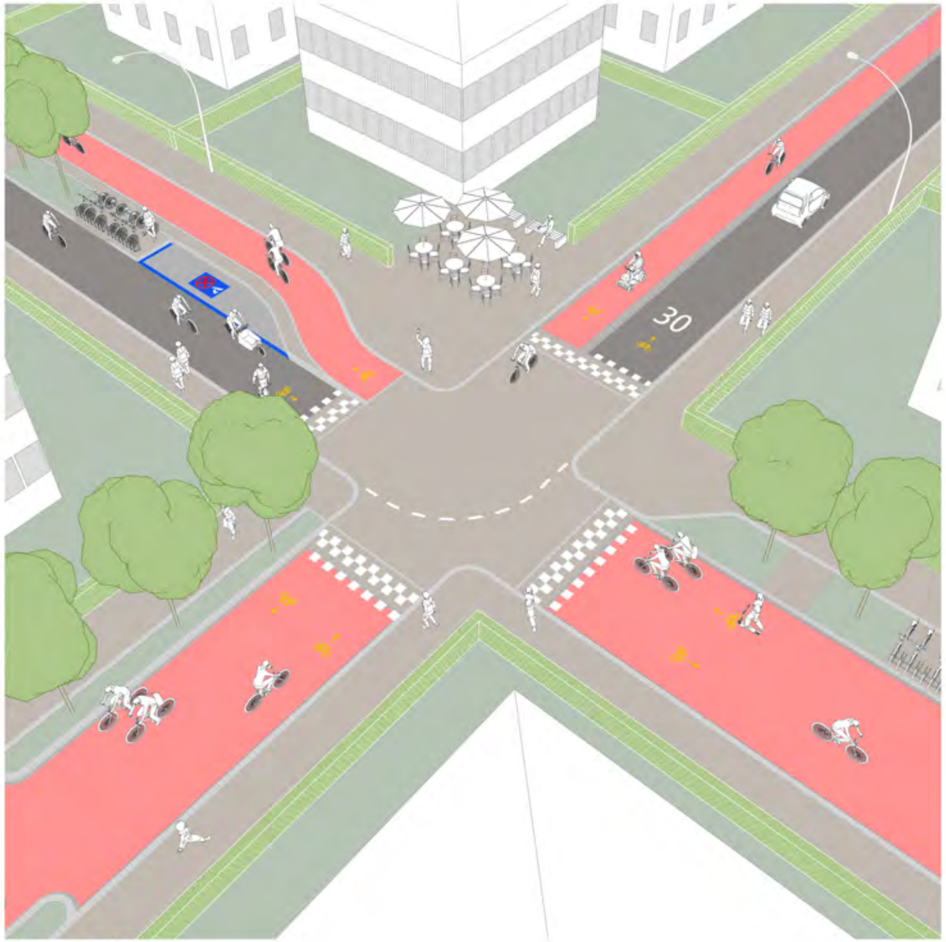
A.8.1.1 RR-Base: Mixed traffic (status quo)



A.8.1.2 RR-A1: Cycling streets and some car lanes



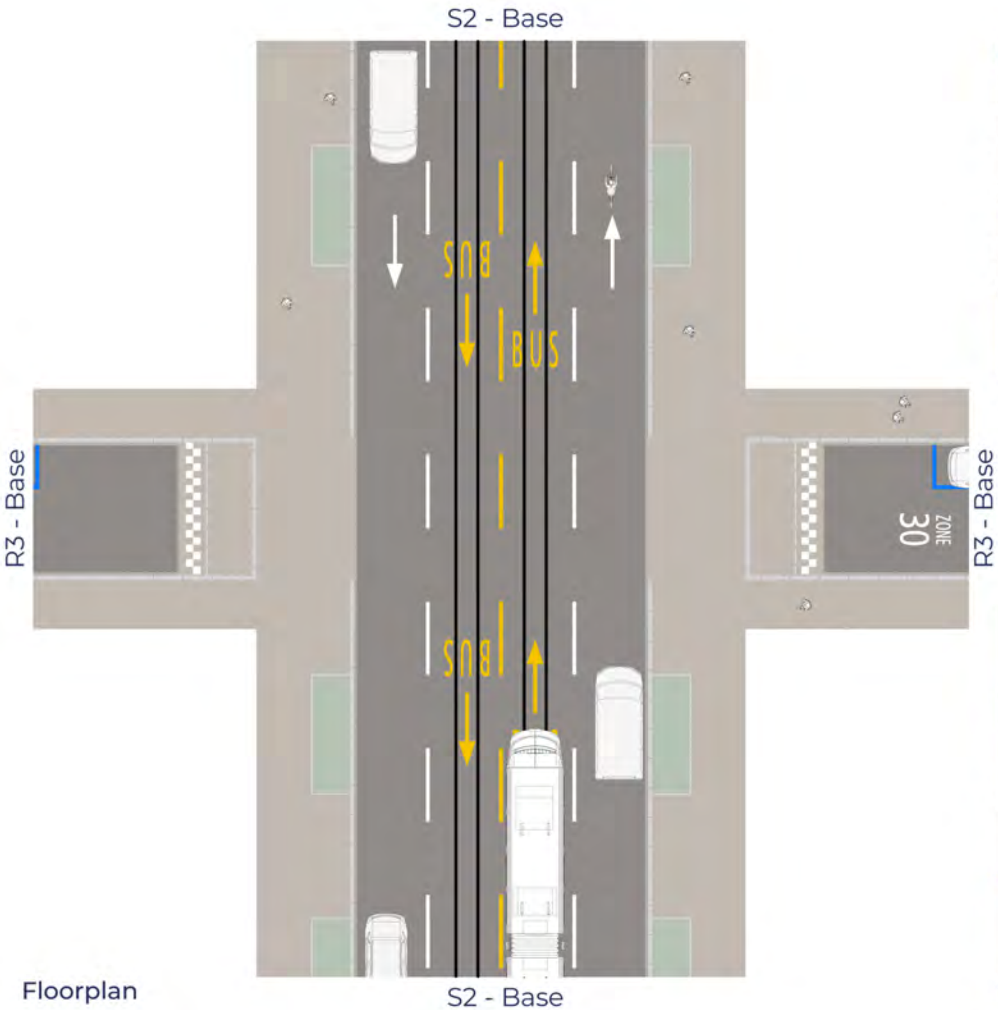
Floorplan



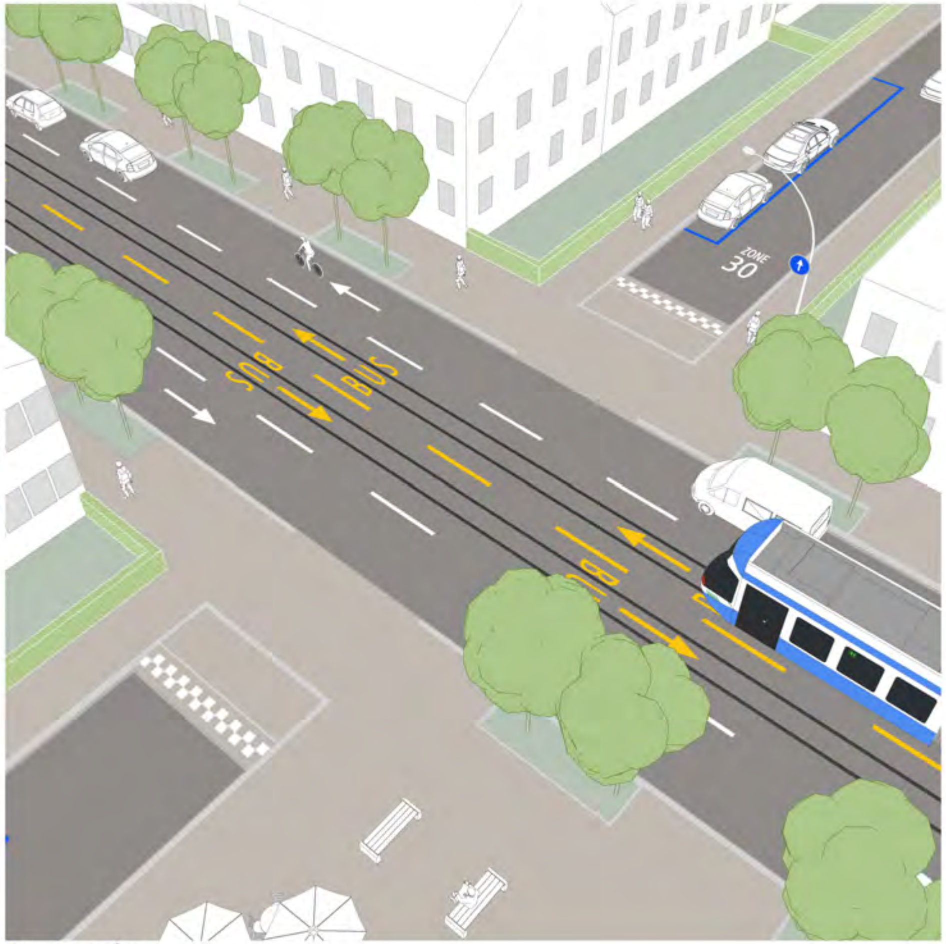
Perspective

A.8.2 SR: Secondary and residential street

A.8.2.1 SR-Base: Mixed traffic (status quo)

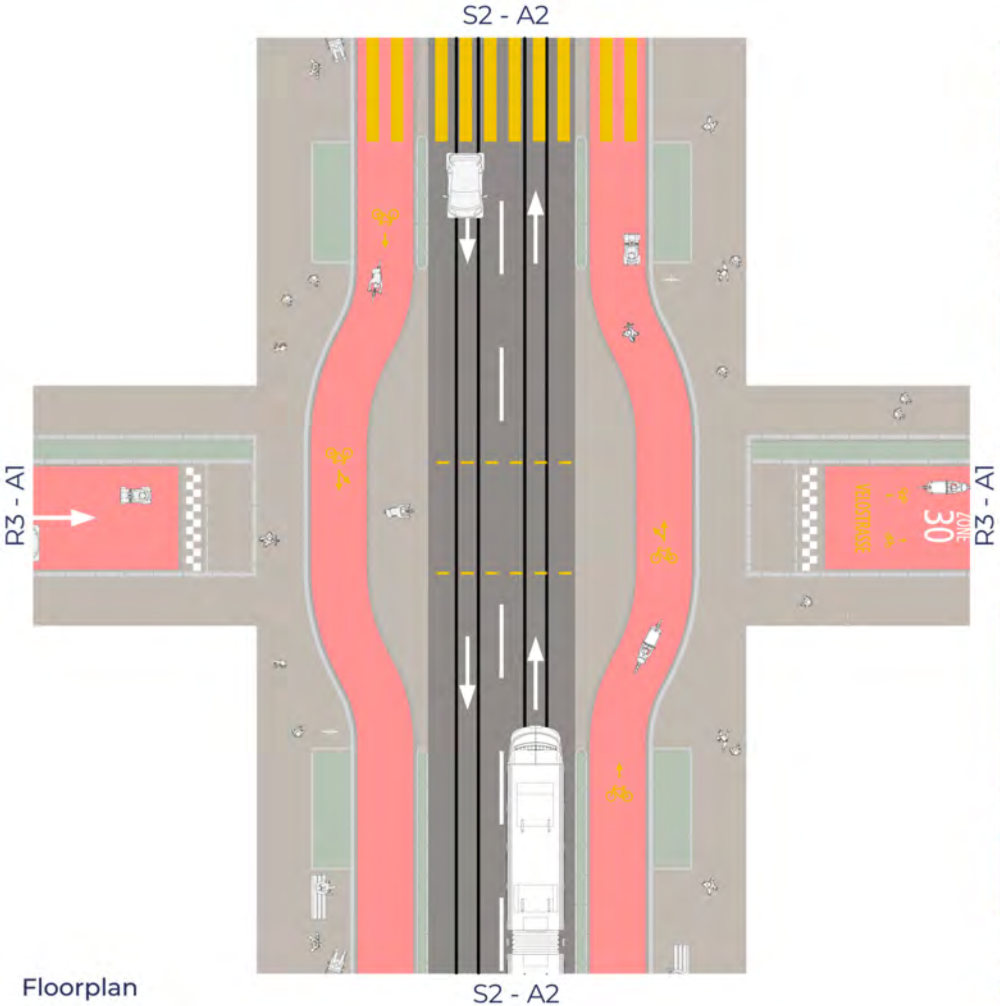


Floorplan

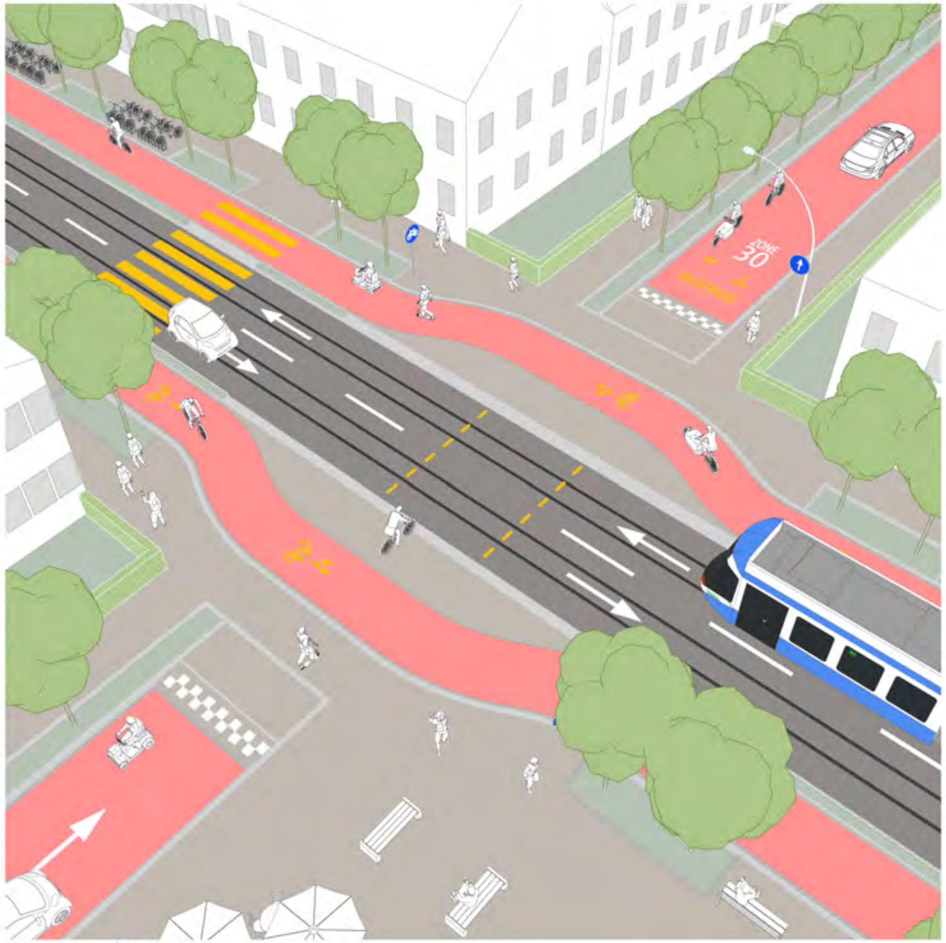


Perspective

A.8.2.2 SR-A1: Separated cycling paths

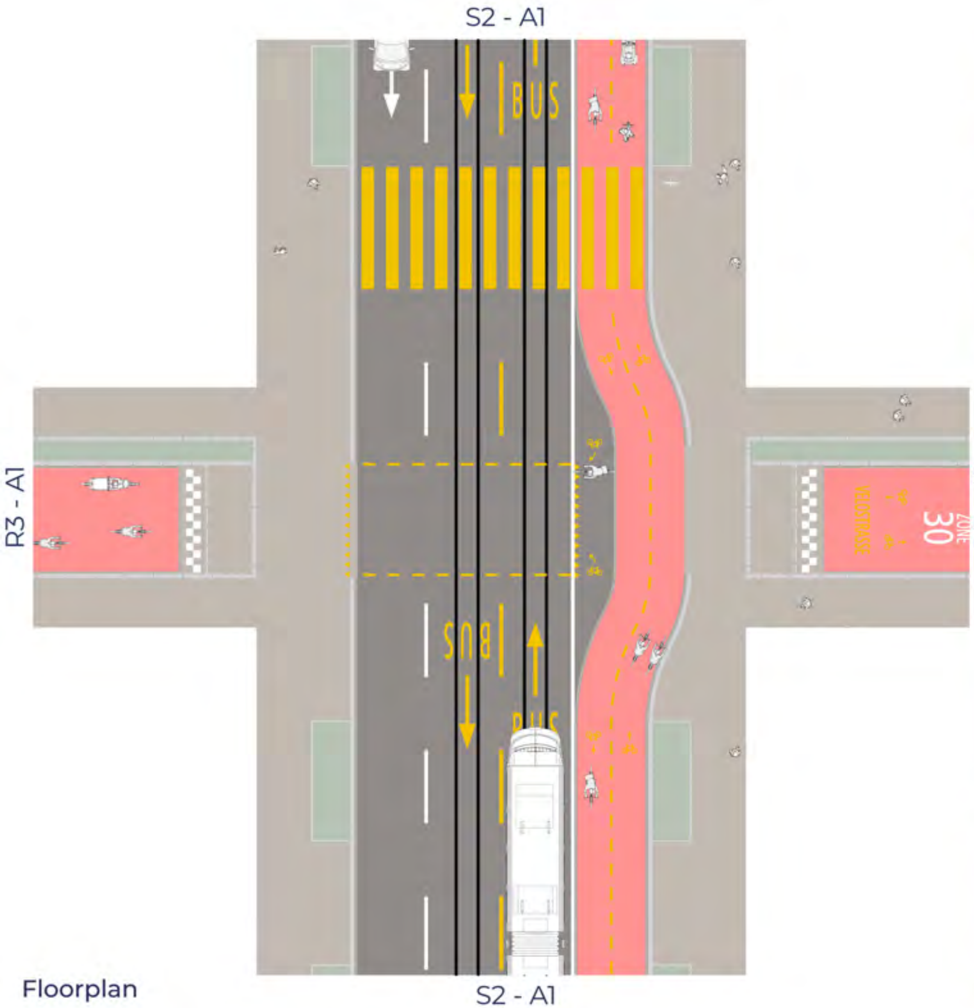


Floorplan

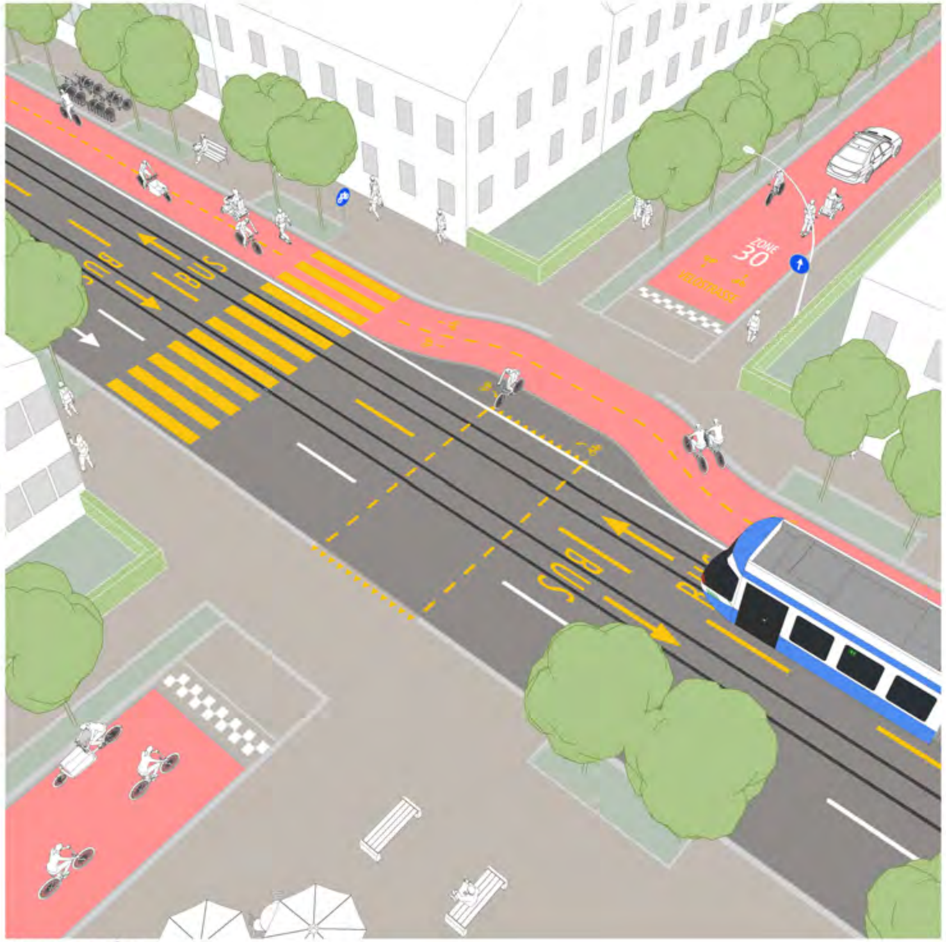


Perspective

A.8.2.3 SR-A3: Separated bidirectional cycling path

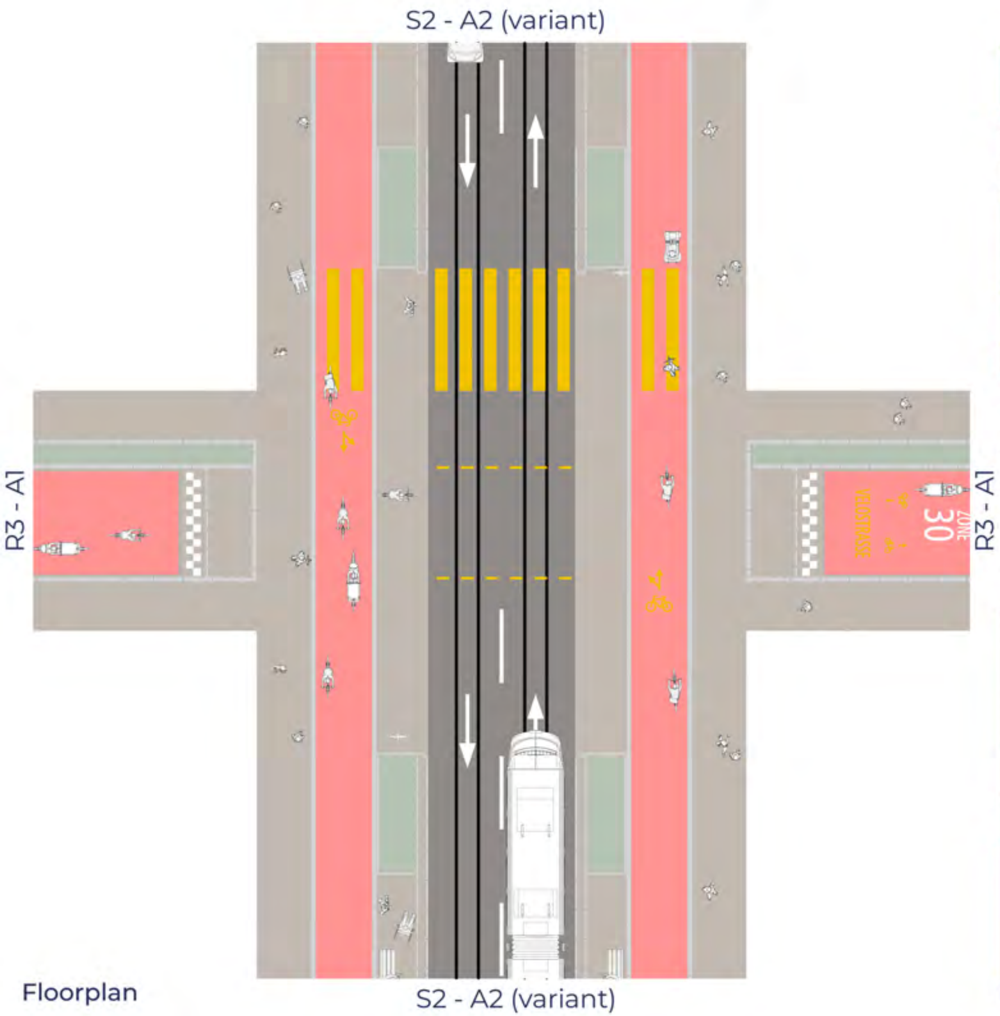


Floorplan

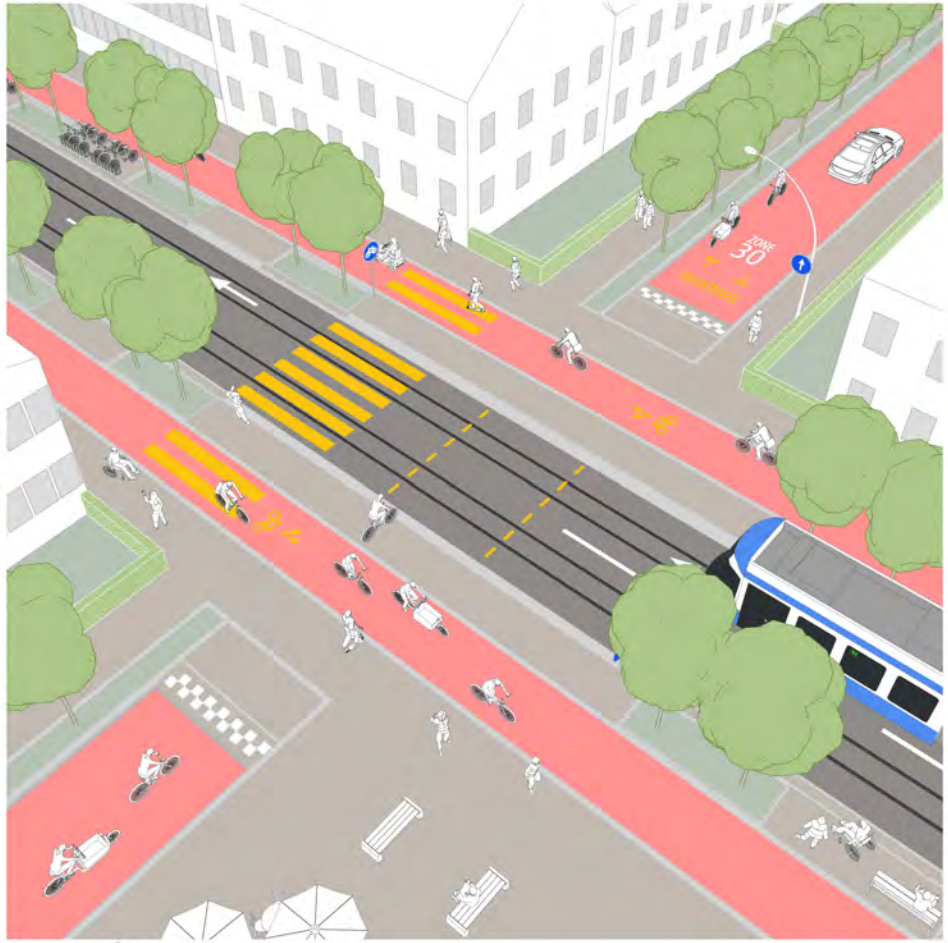


Perspective

A.8.2.4 SR-A2: Separated and protected cycling paths



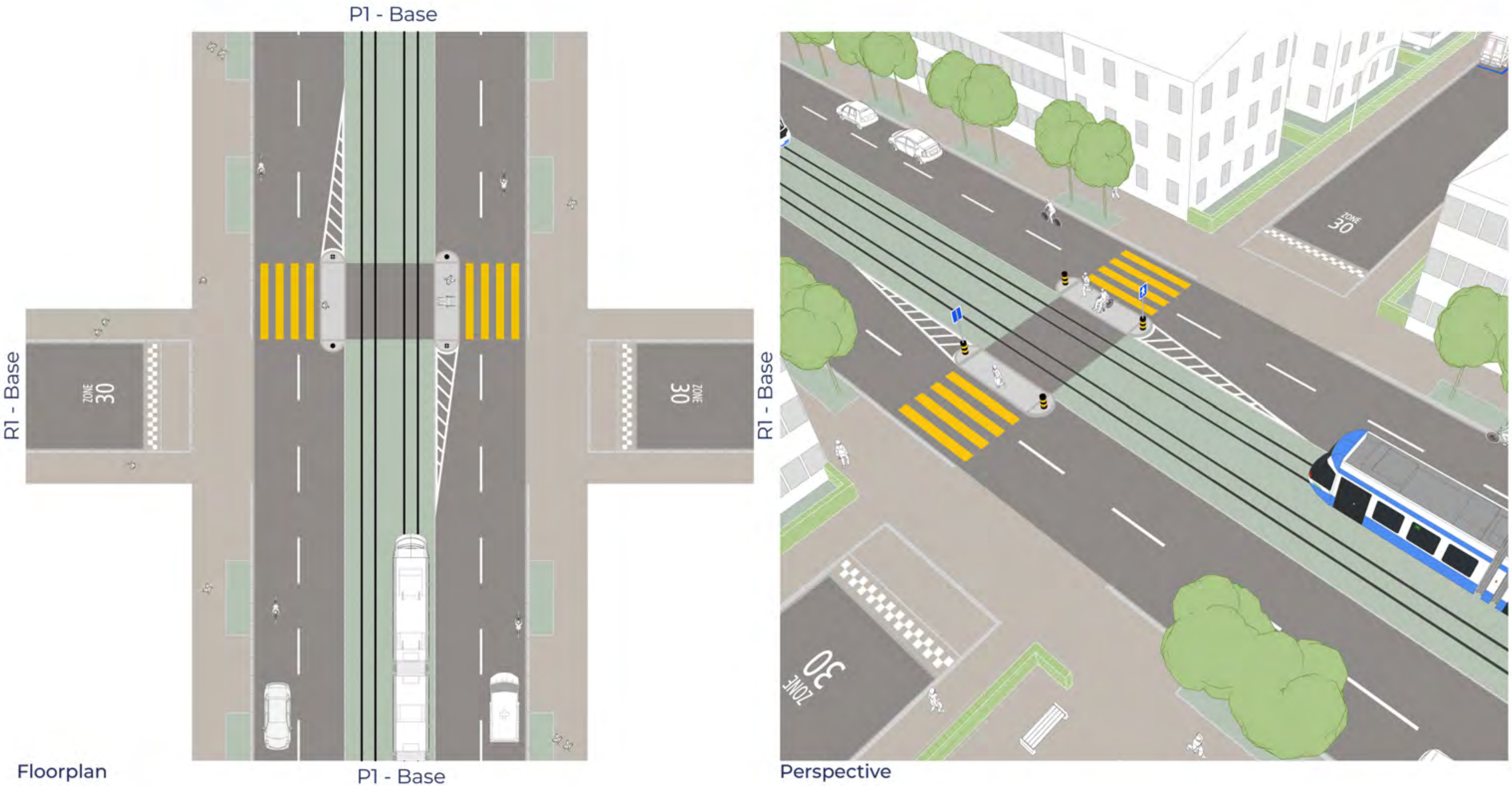
Floorplan



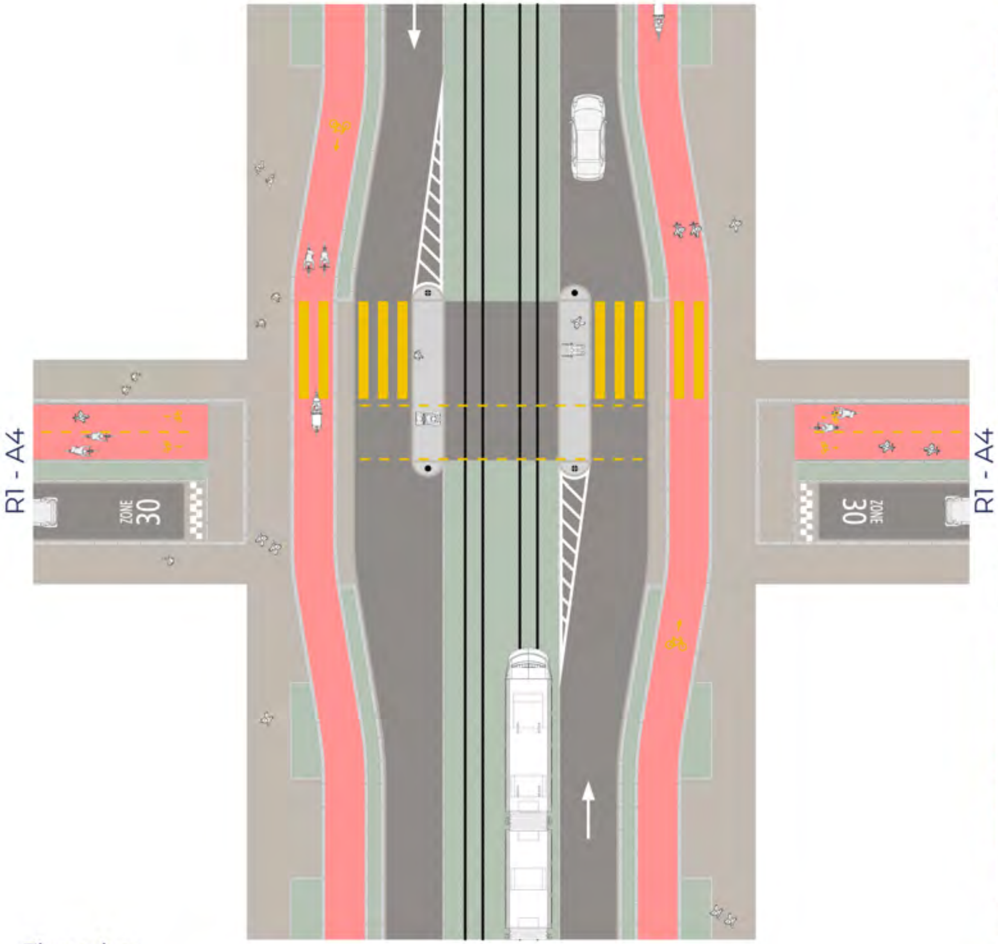
Perspective

A.8.3 PR: Primary and residential street

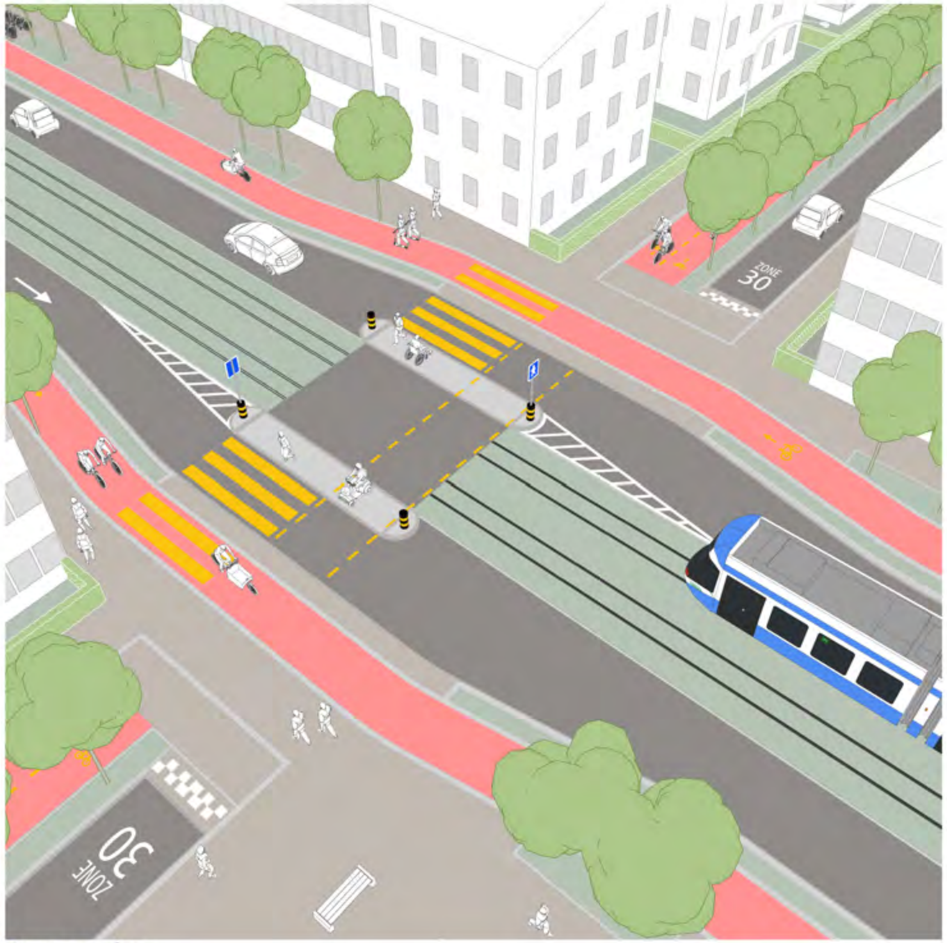
A.8.3.1 PR-Base: Mixed traffic (status quo)



A.8.3.2 PR-A2: Separated cycling paths

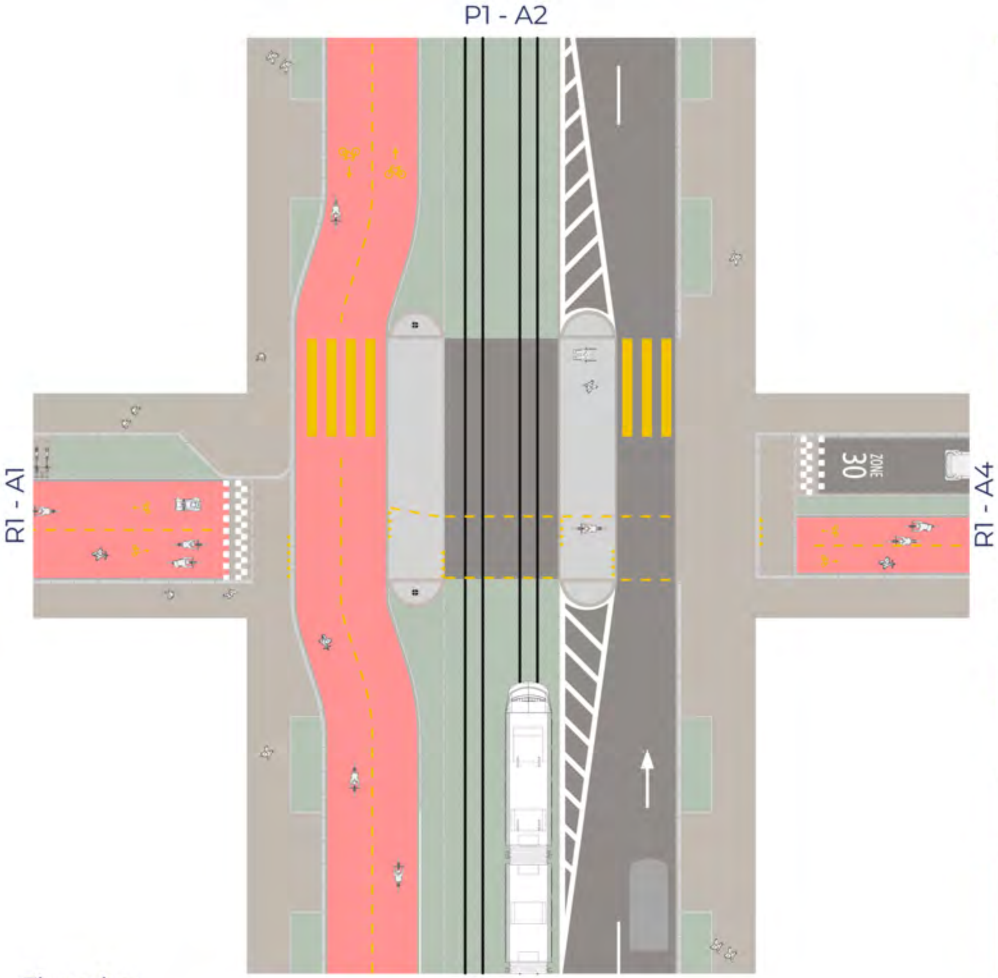


Floorplan

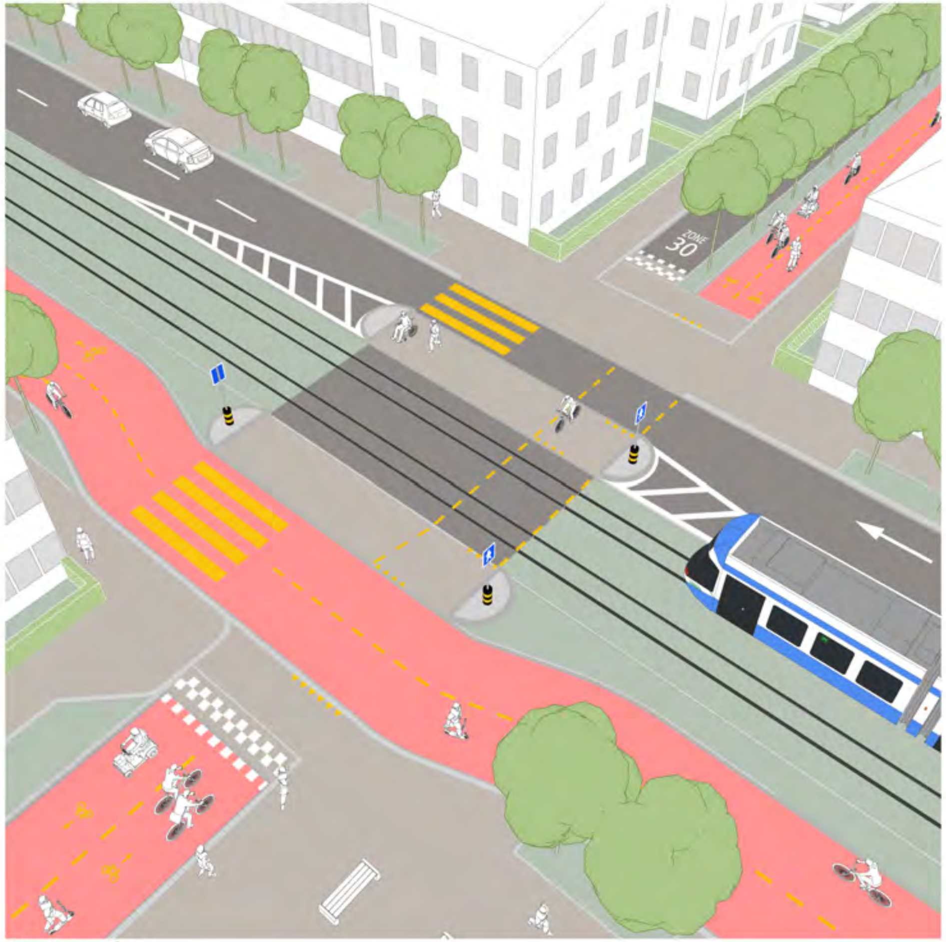


Perspective

A.8.3.3 PR-A1: Separated bidirectional cycling path



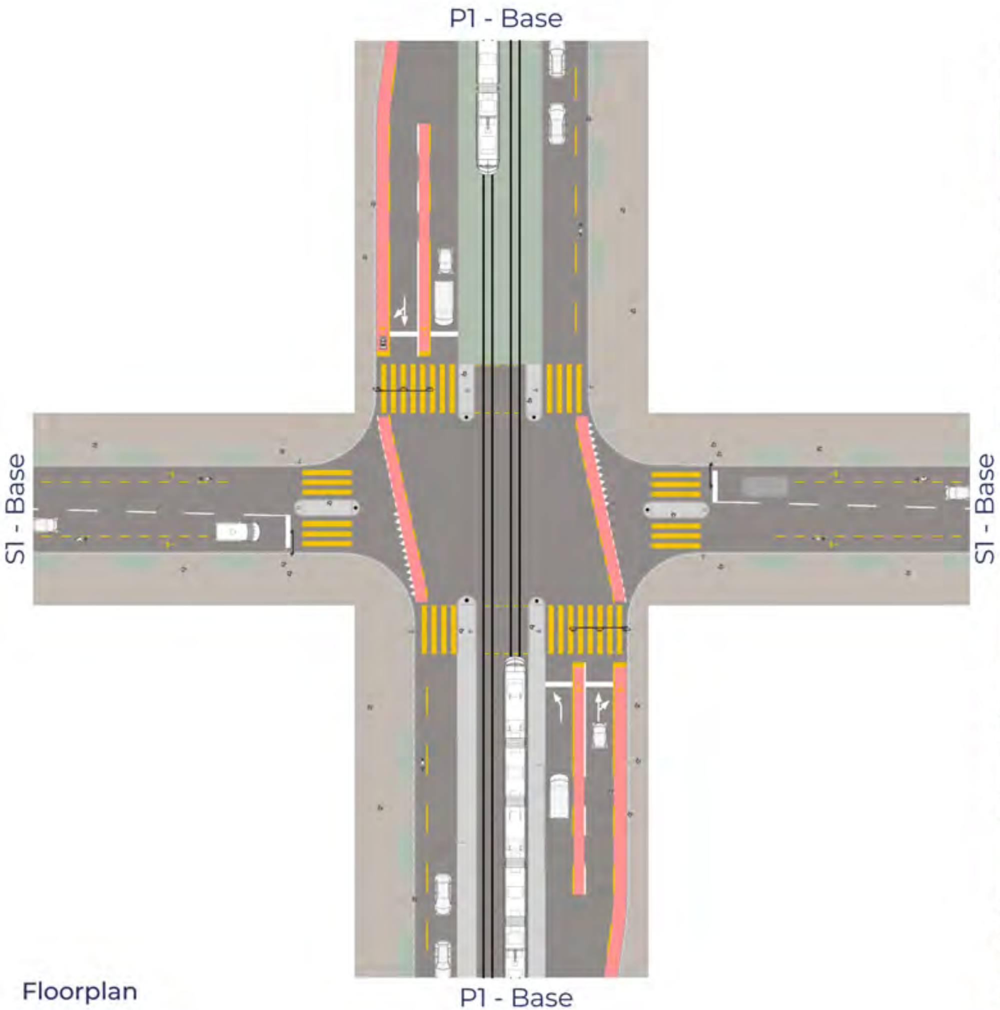
Floorplan



Perspective

A.8.4 PS: Primary and secondary street

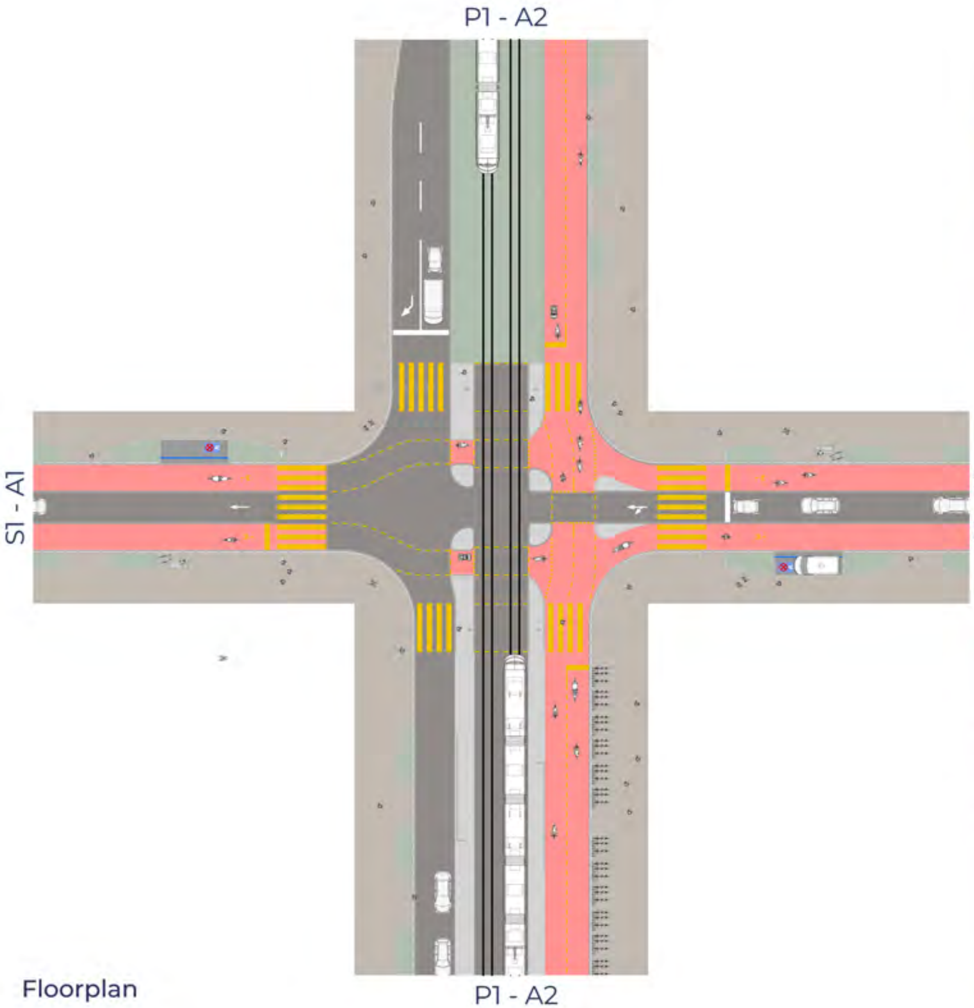
A.8.4.1 PS-Base: Mixed traffic (status quo)



Floorplan

Perspective

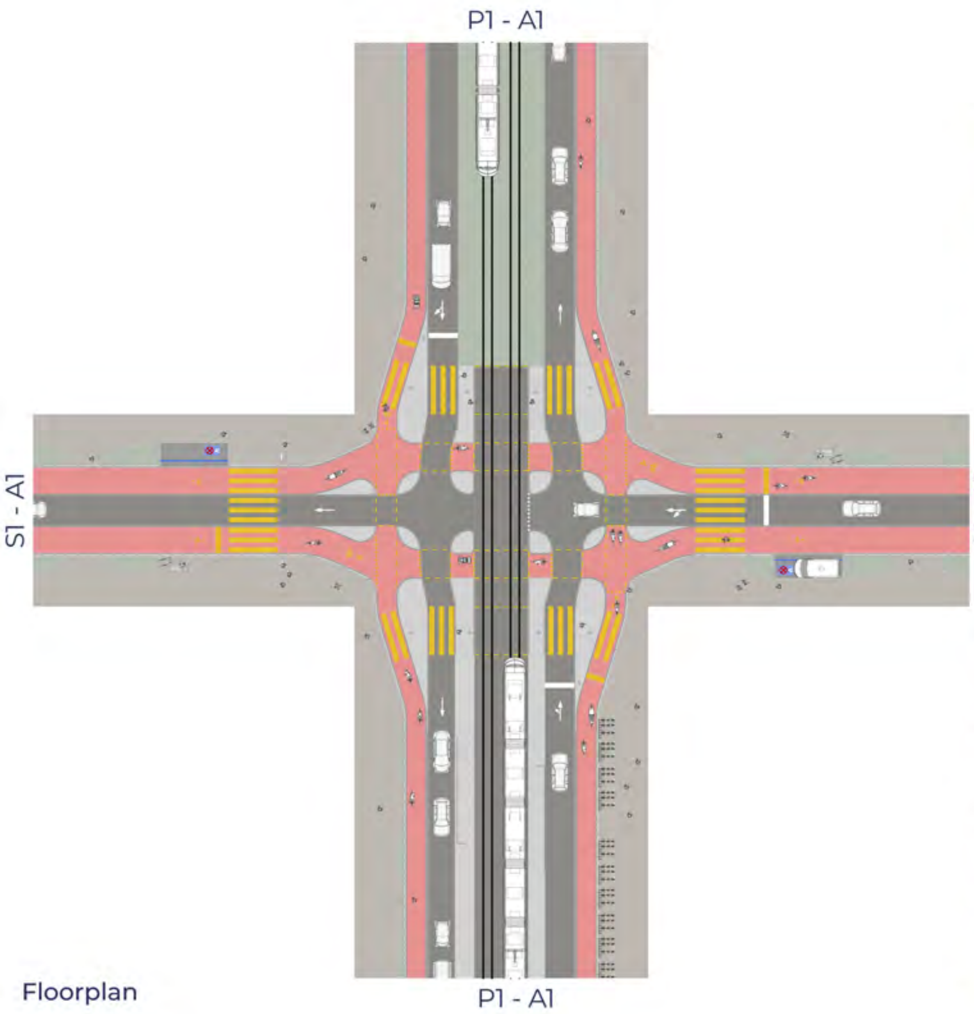
A.8.4.2 PS-A1: Separated cycling paths



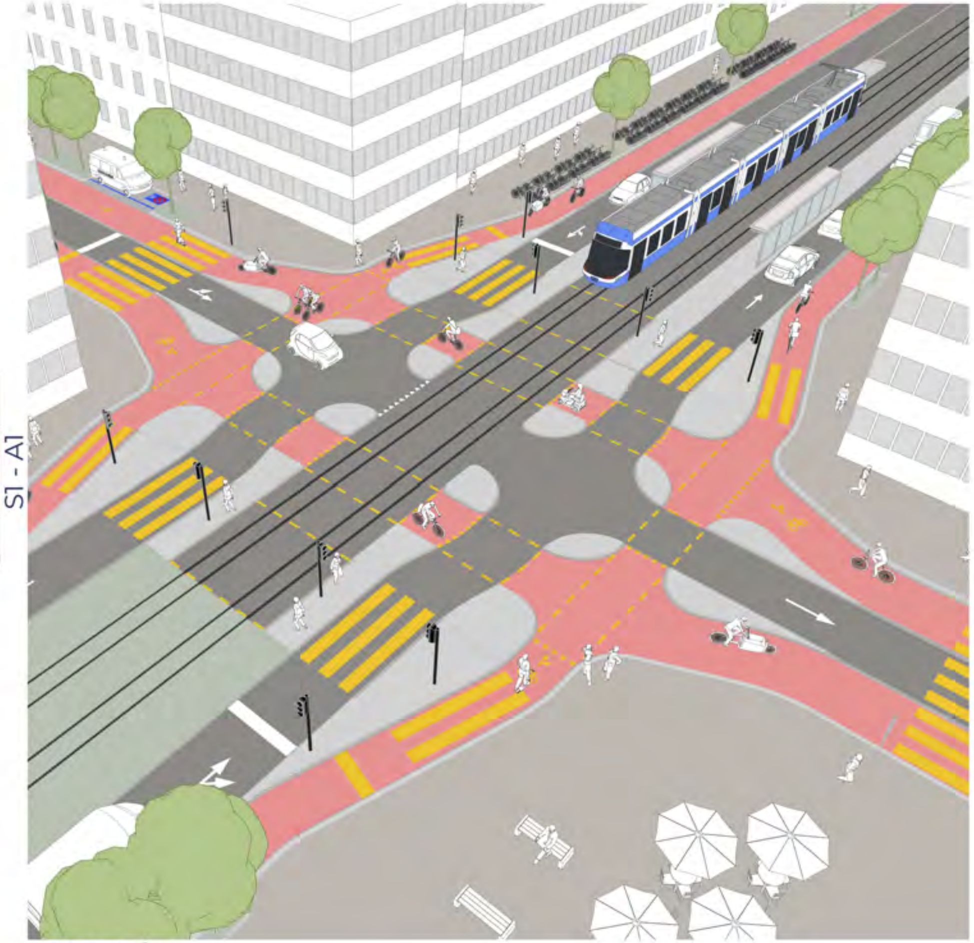
Floorplan

Perspective

A.8.4.3 PS-A2: Separated and protected bidirectional cycling path



Floorplan



Perspective

Chapter B: Appendix: Preparing the CAD Models

Creating Scenes in Vectorworks

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2024-02-15

1. Introduction

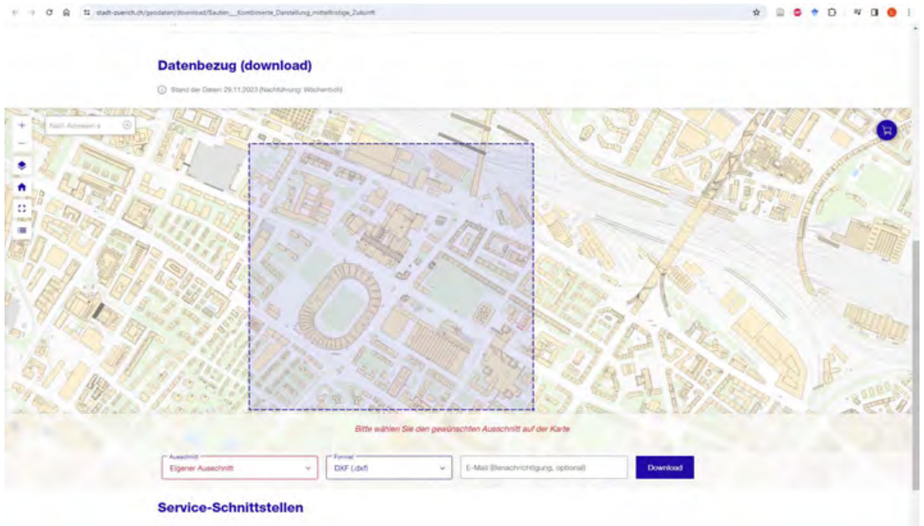
This document explains how you can create new scenes (roads, buildings, etc.) for your designs in Vectorworks from the official land surveying data in Zurich.

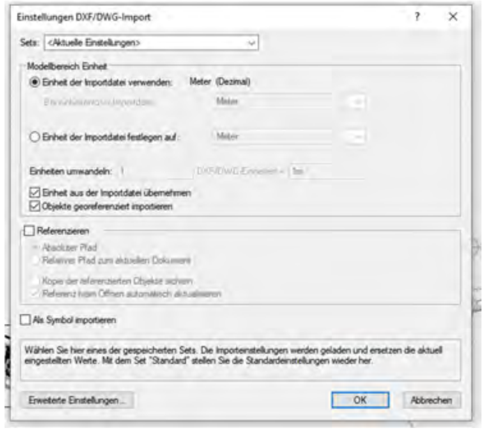
Open the ebc_library_only.vwx file. It contains multiple designs that have been already done and you can copy the design elements from it. It also has multiple layouts with cameras, as well as geo referencing.

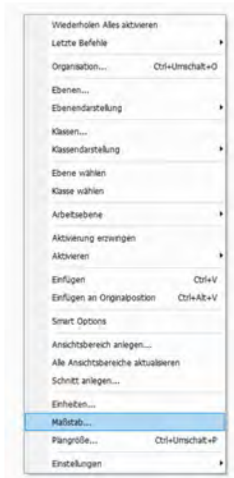
2. Adding 3D buildings

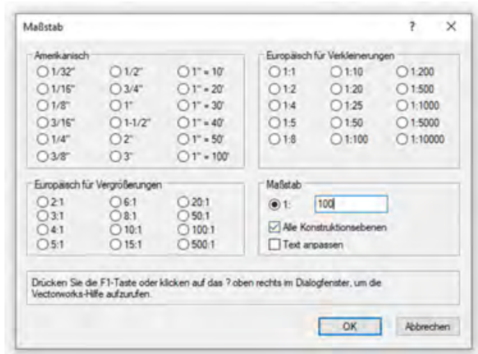
Download the 3D buildings here:

https://www.stadt-zuerich.ch/geodaten/download/Bauten___Kombinierte_Darstellung_mittelfristige_Zukunft

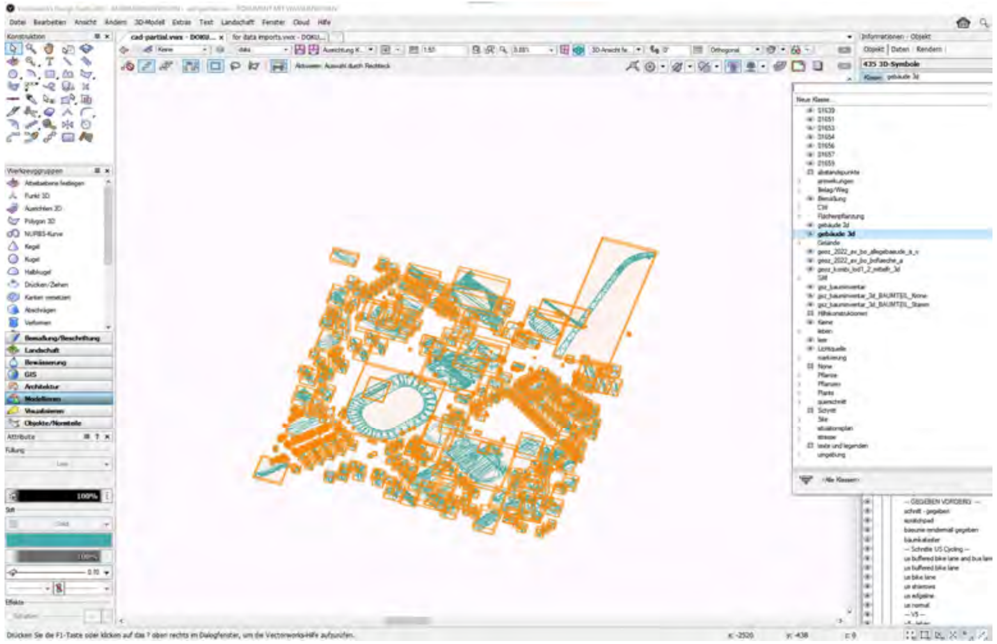




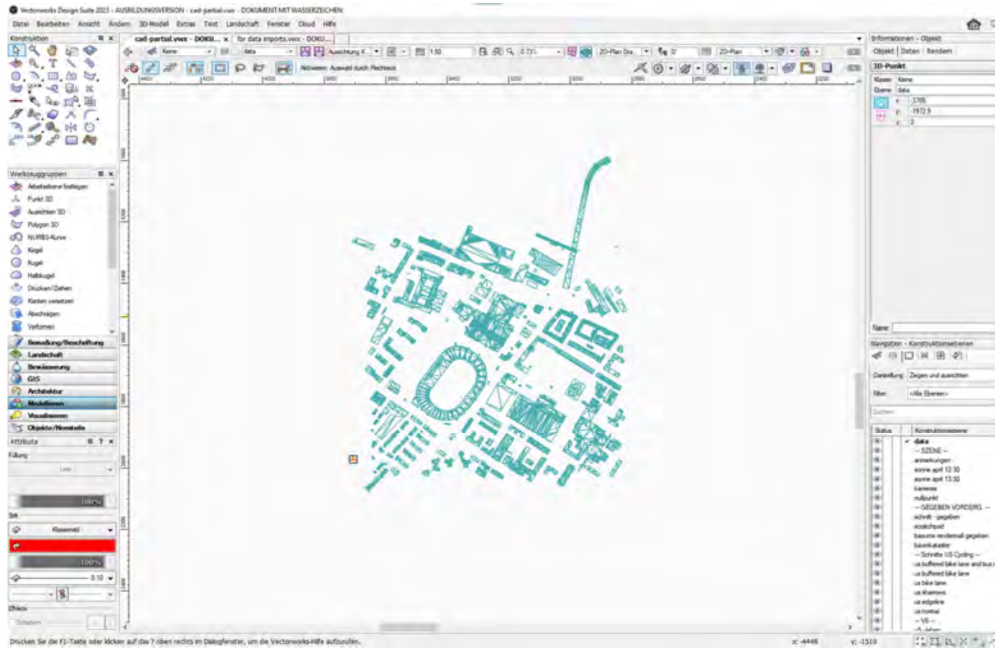




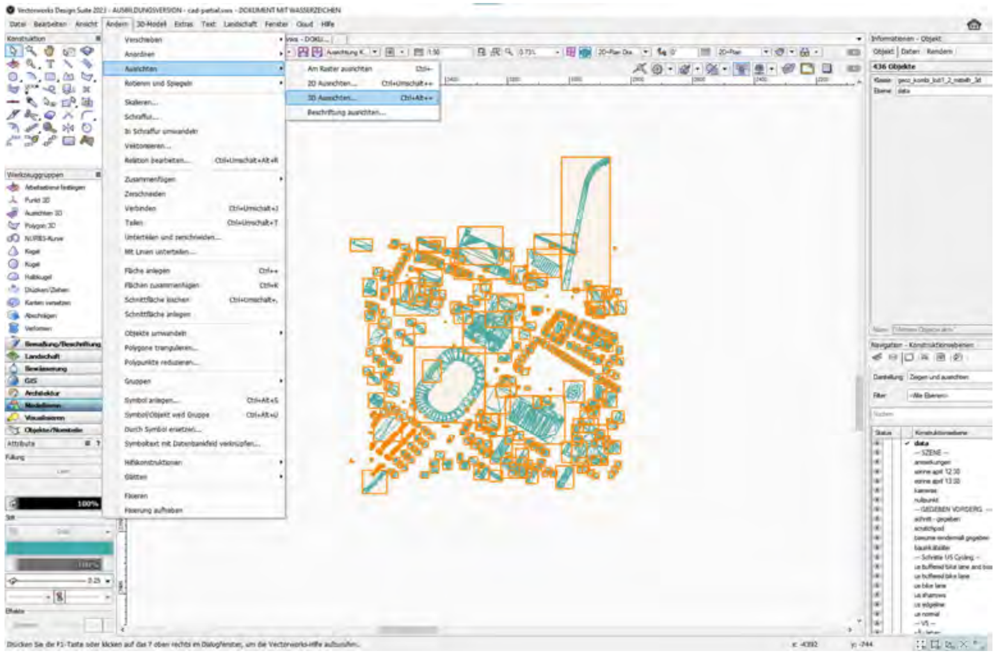
Change the class of all the new 3D buildings to ‘gebaude 3d



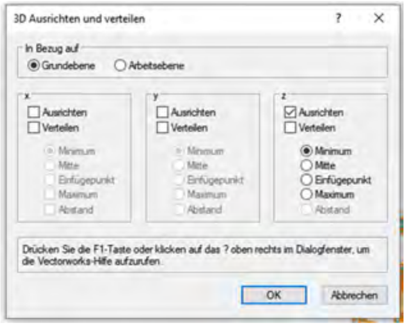
Add a 3D Point and make sure its z-value is 0



Select all object using the rectangle selection tool and click ‘3D Ausrichten’

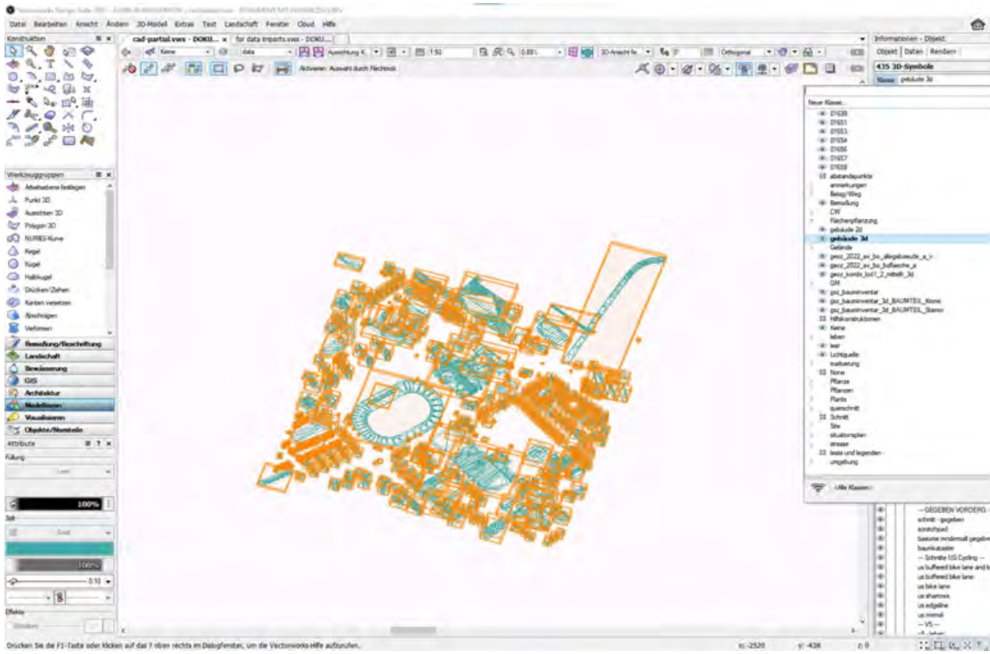


Move all building object to z

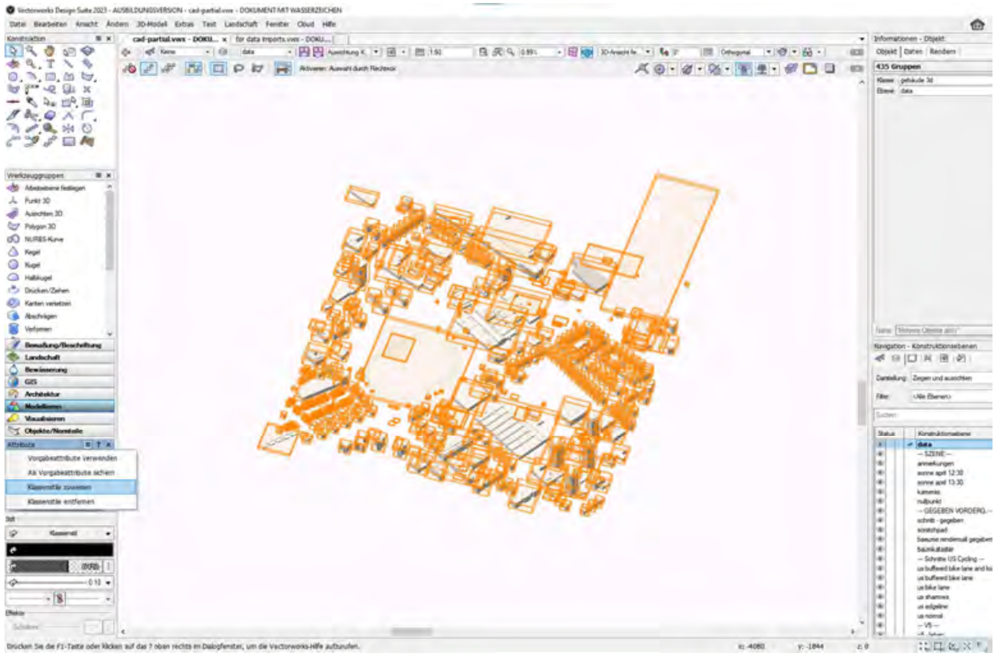


Click OK and then delete the 3D point

Change the class of all the new 3D buildings to 'gebaude 3d. If asked whether it should apply to al objects in groups, confirm yes.



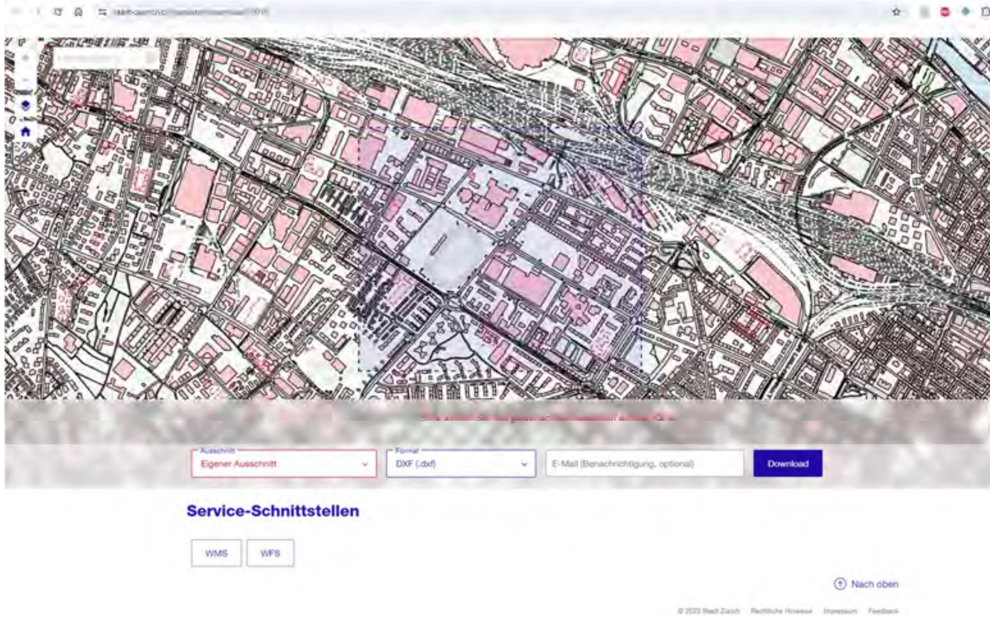
Apply the class styles to all selected buildings

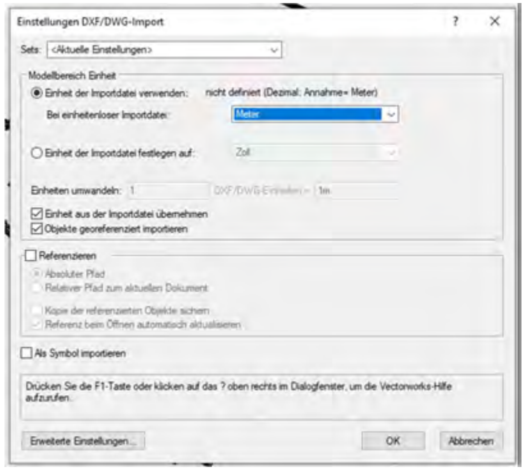


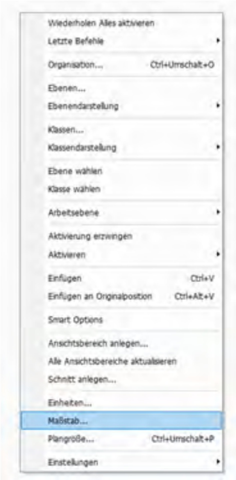
3. Adding official survey data

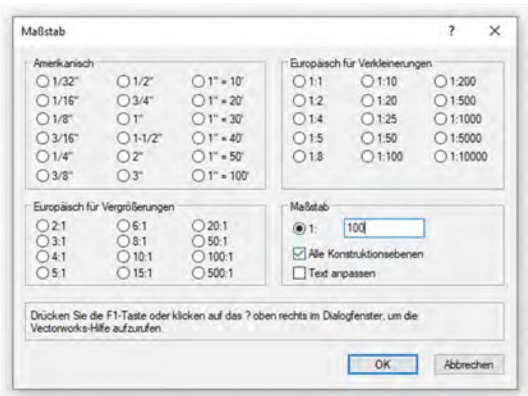
Download the data:

https://www.stadt-zuerich.ch/geodaten/download/10016

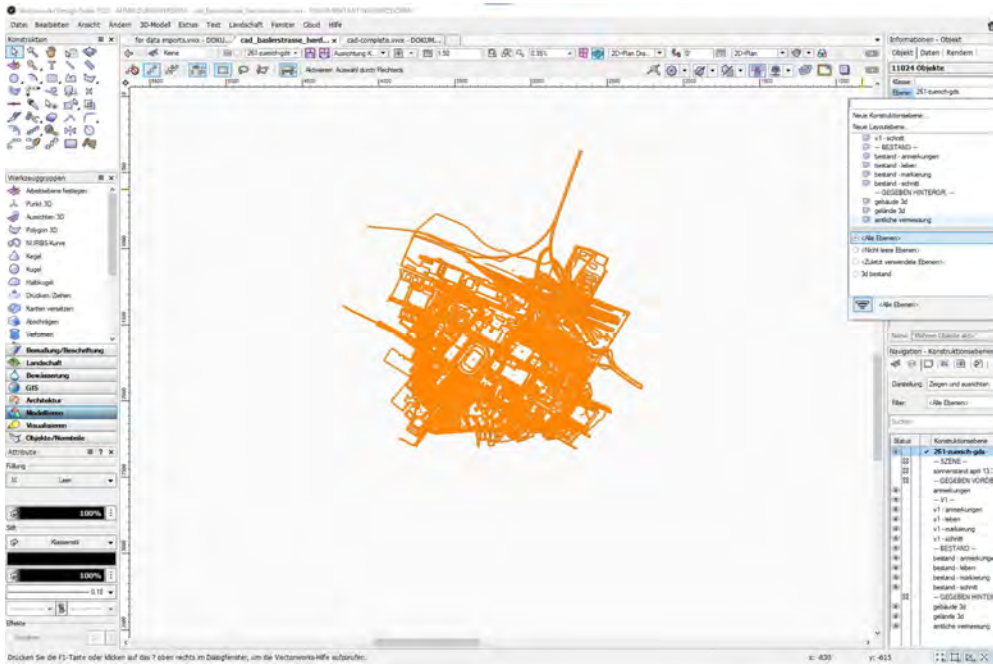








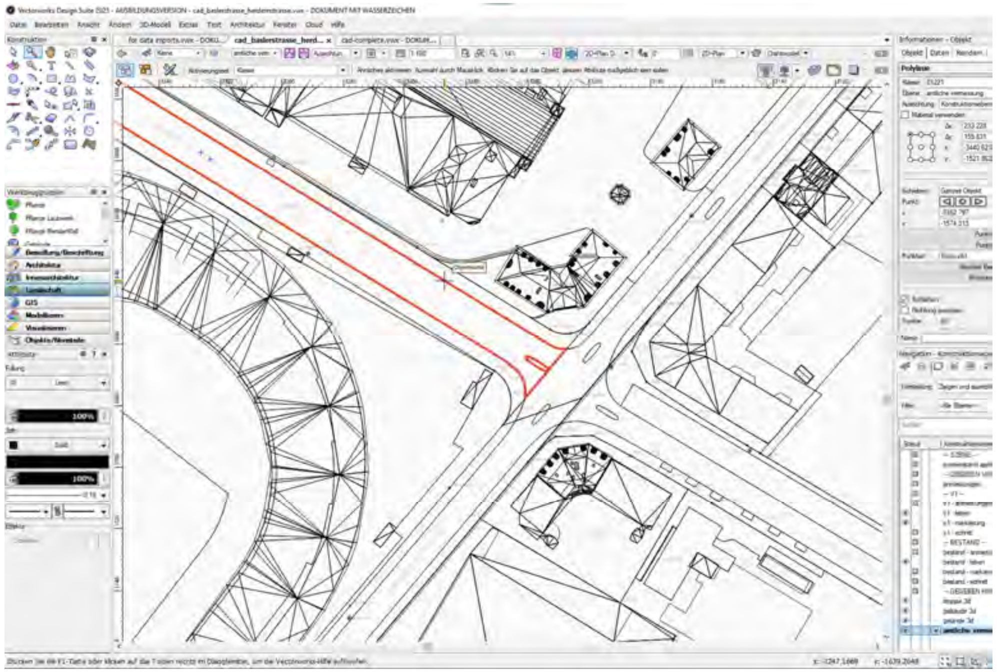
Move the imported objects into the layer “amtliche vermessung”. But don’t change the classes.



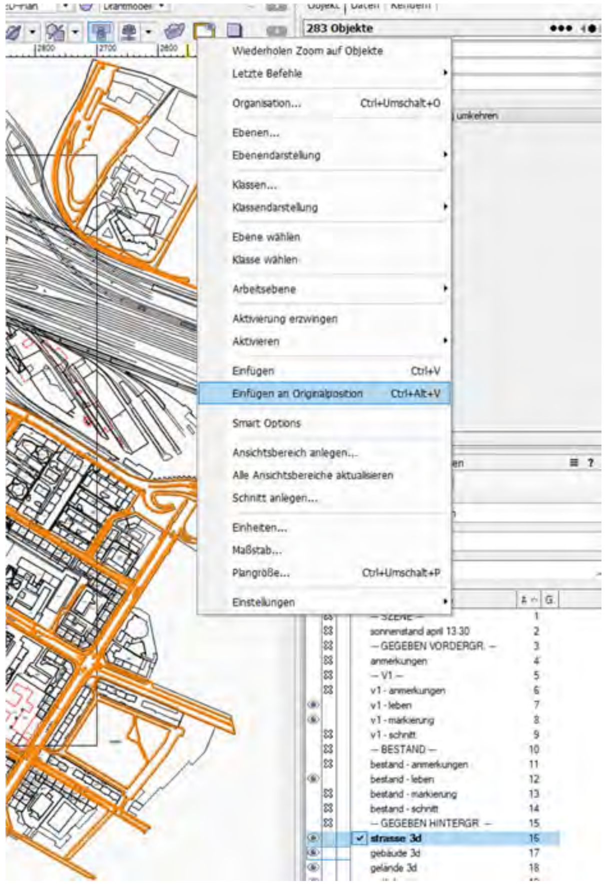
Now, you can delete the imported layer.

4. Converting survey data into street objects

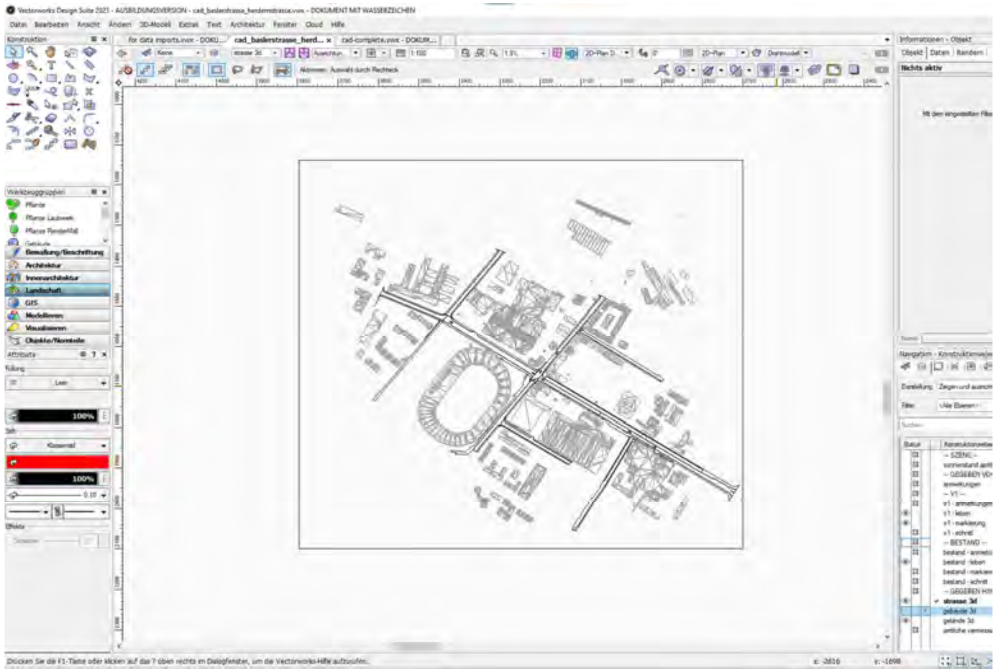
Activate ‘amtliche vermessung’ and find a street object with the class 01221. Use the tool ‘ähnliches Objekt aktivieren’, change the Aktivierungsset to ‘Klasse’ and click on the object you found before. This will select all objects with the same class. Then, copy these objects using Ctrl+C.



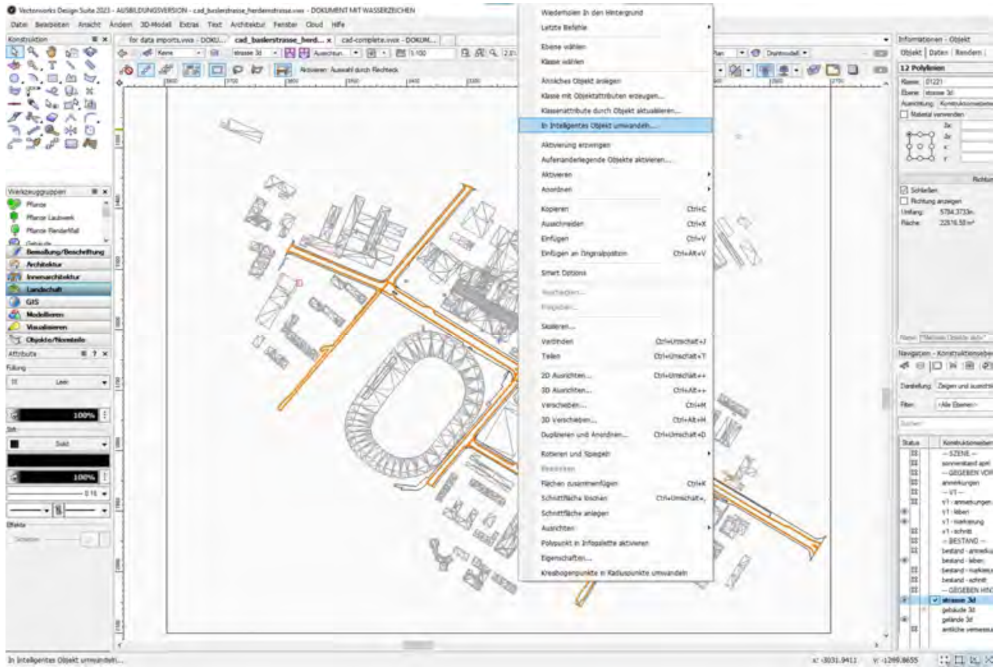
Activate the layer 'strasse 3d' and paste the objects in the original position using Ctrl+Alt+V



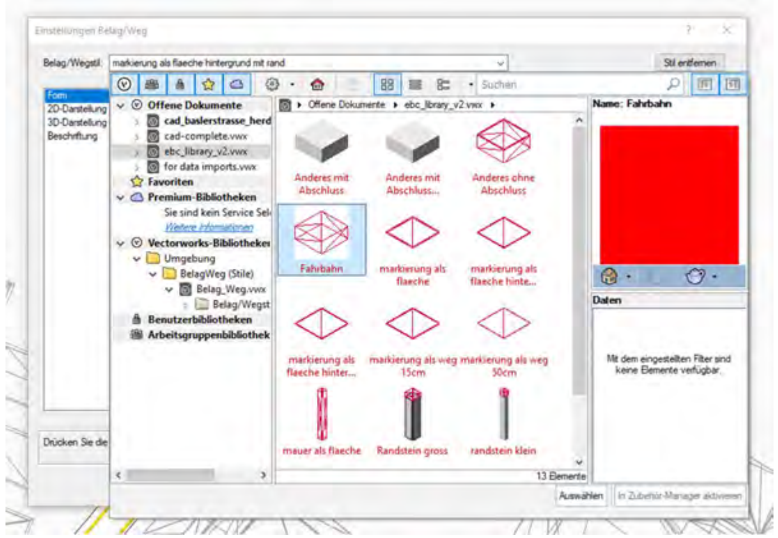
Remove all streets that you will not need



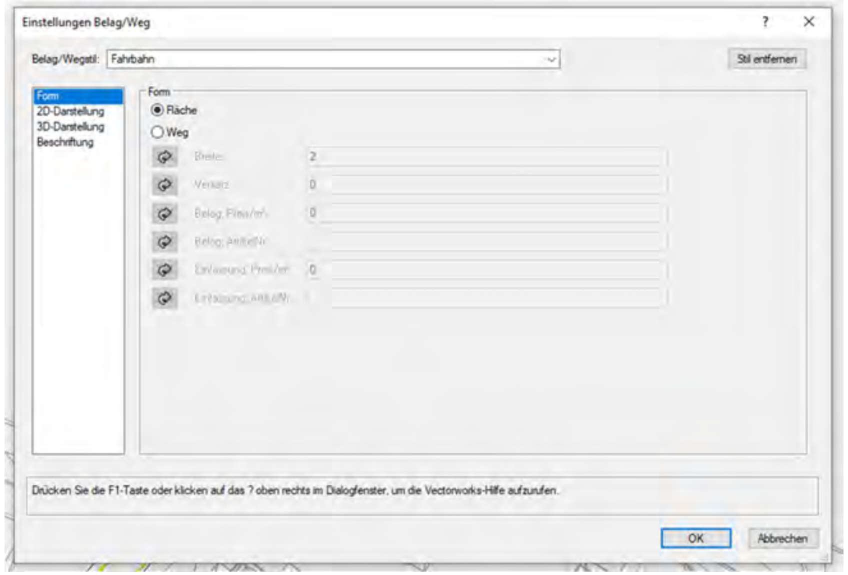
Select all elements that belong to the actual road pavement, not sidewalks, right click and select ‘in intelligentes Objekt umwandeln’



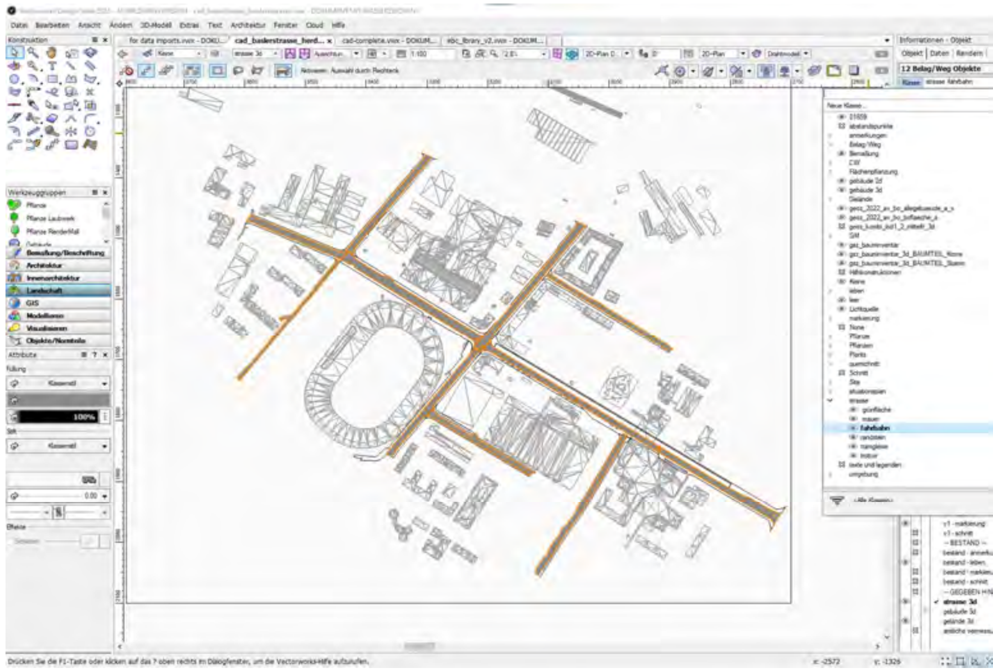
Make the following choices in the window:



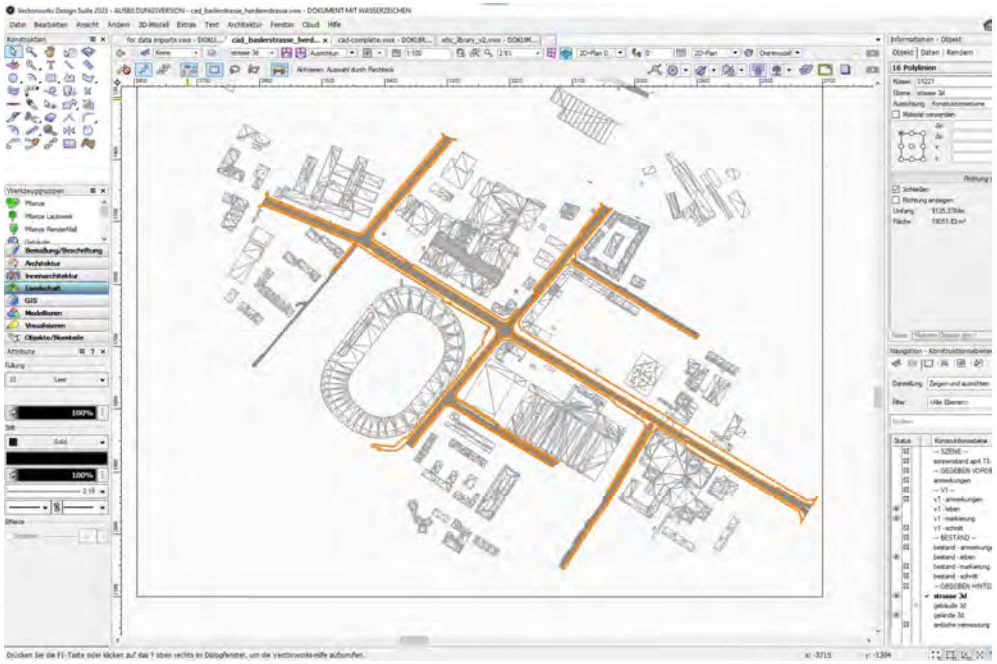
Make sure the Form ‘Fläche’ is selected:



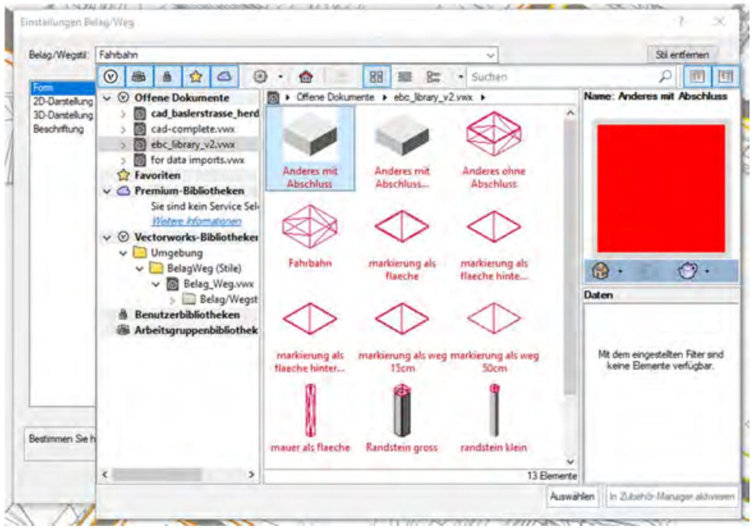
Change the class of the objects to ‘strasse-fahrbahn’



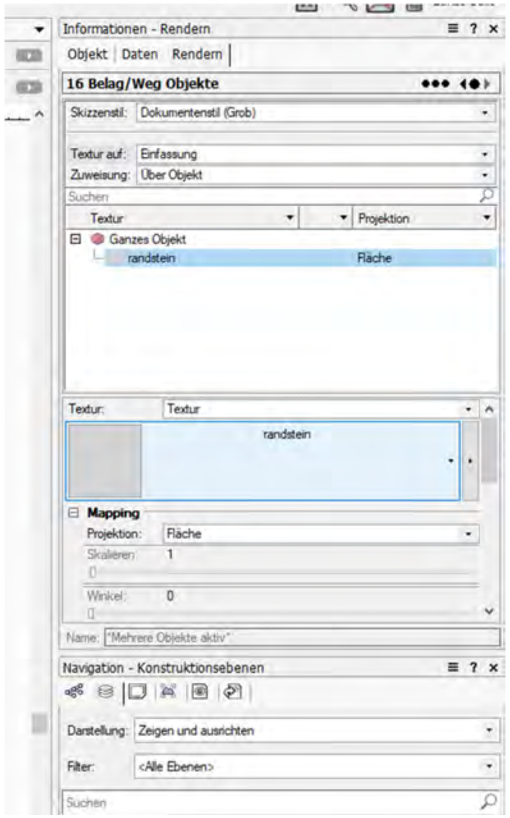
Select all objects that belong to sidewalks and consolidate them using Ctrl+K



Convert to intelligent objects and select ‘anderes mit Abschluss’. Afterwards, make sure the form ‘Fläche’ is selected.

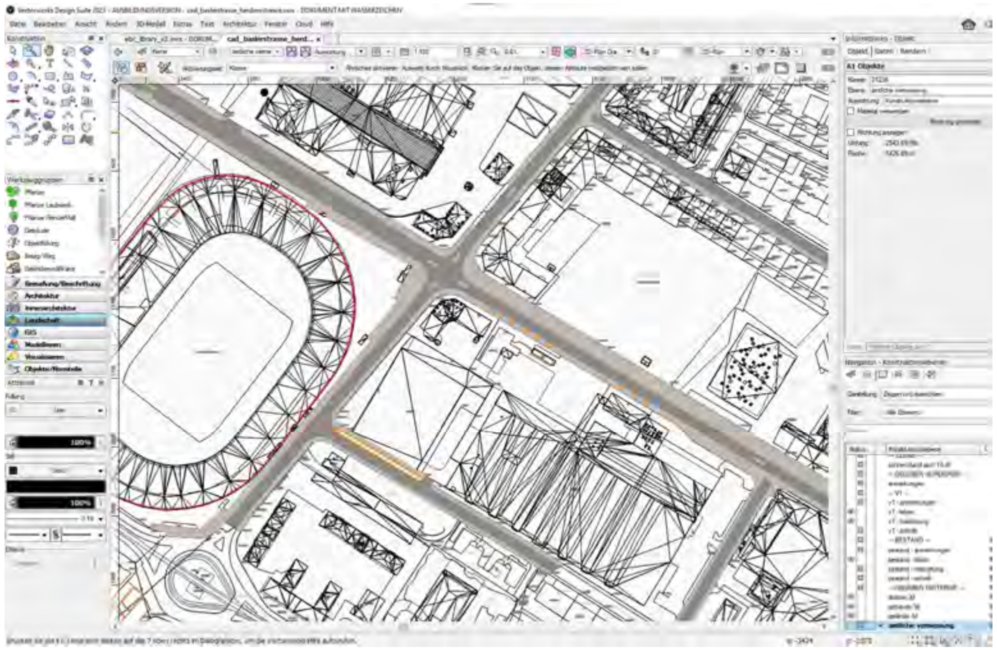


Bug Workaround. Since roughly 2023 there is a bug that leads to a wring representation of the curbstones in 3D. Instead of being in the class ‘strasse-randstein’, they follow the class of the sidewalk, which means they are not visible. To fix it, select all sidewalk objects and change their properties under ‘Redern’ as follows:



4.1 Adding greenery surfaces

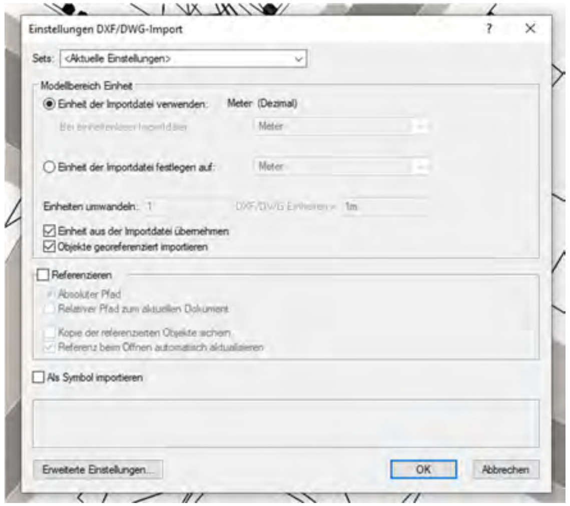
Repeat the same as for the sidewalks but with class 01236. When selecting the intelligent object, choose ‘Anderes ohne Abschluss’ and assign the objects to the class ‘strasse-grünfläche’.



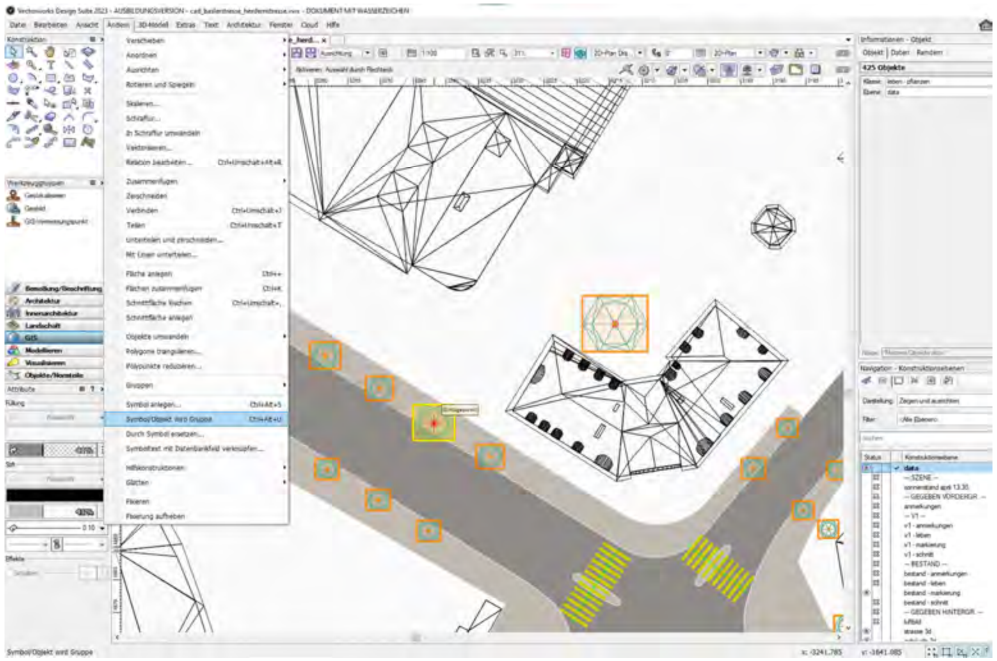
5. Adding trees

Download the 3D trees from here: https://www.stadt-zuerich.ch/geodaten/download/Bauminventar. Limit the region to the minimum that you need.

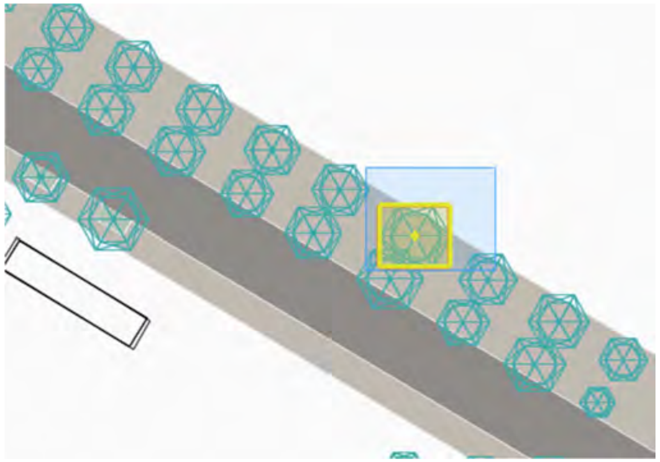
Import the objects, check ‘Objekte georeferenziert importieren’



Remove all points from the dataset. Second, convert all symbols to groups

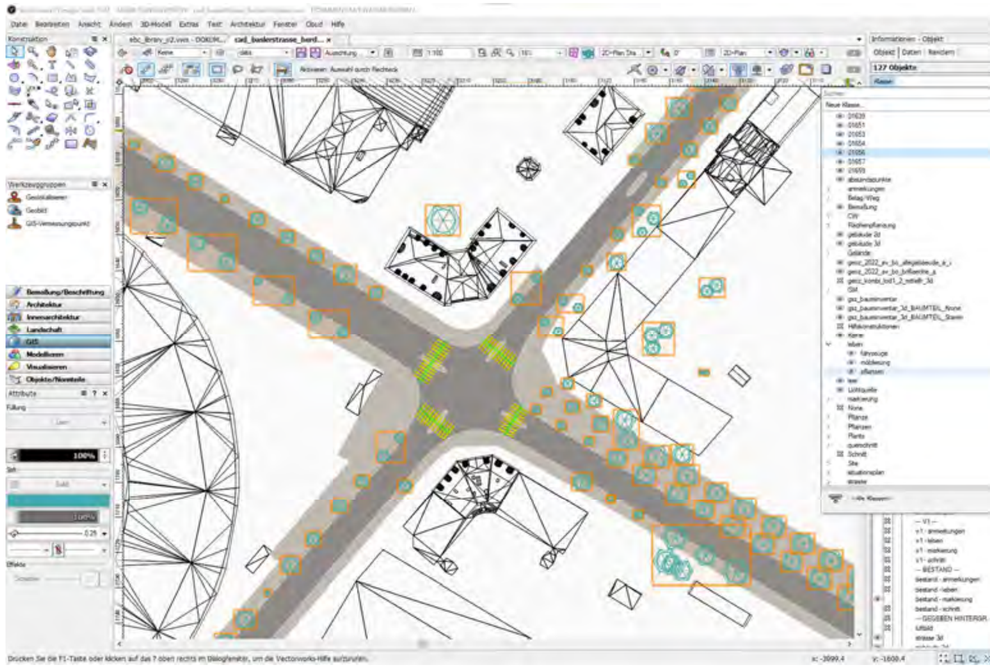


Second, group each tree or a small set of trees with their stems. This will take some time but is important to properly level all trees at z=0.

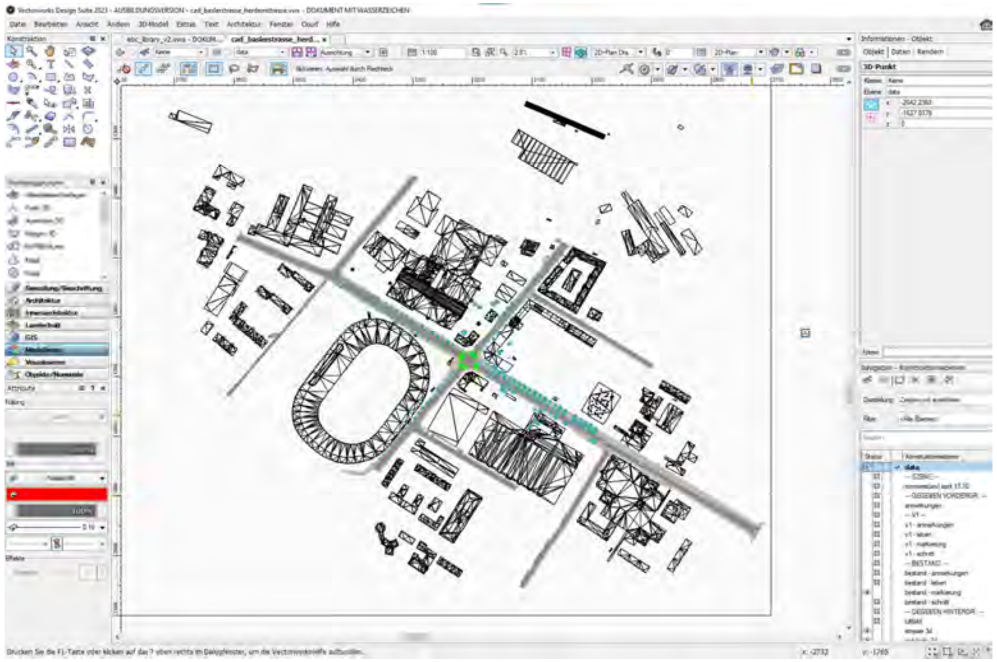


creating_scenes_in_vectorworks .01 lba.docx

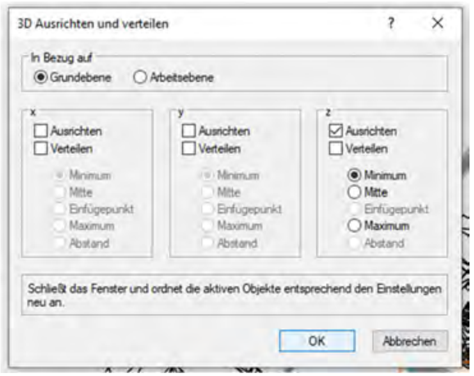
Select all grouped trees, move them into the class leben-pflanzen and apply class styles.



Add a 3d point, make sure z is zero.

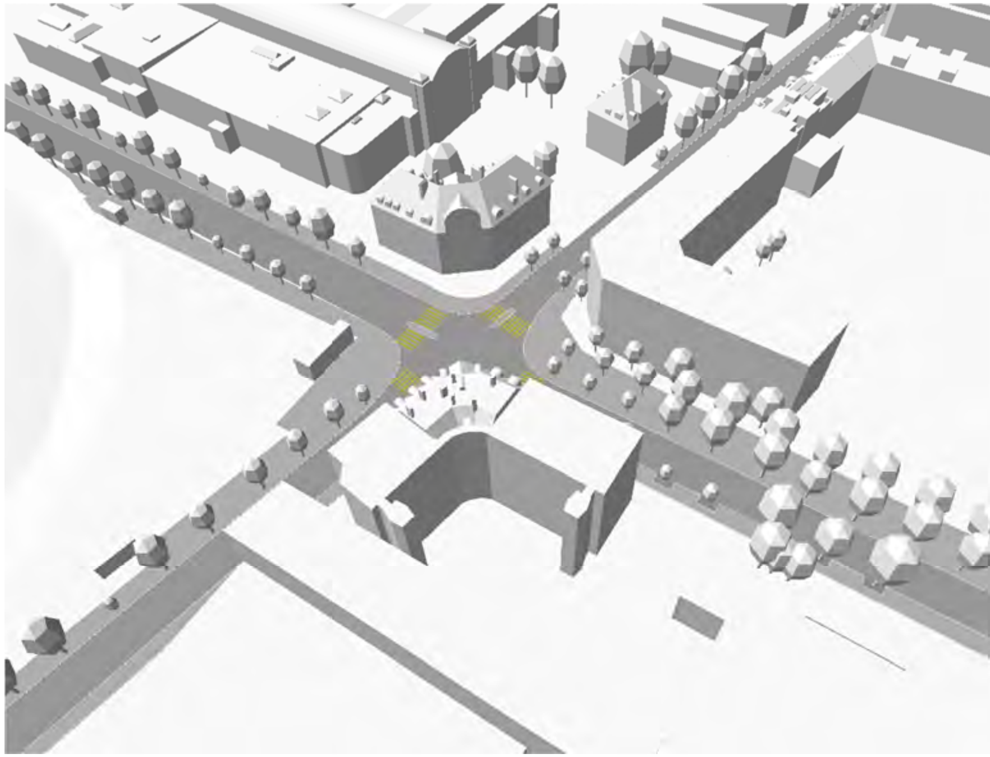


Select all the trees and the 3d point and use ‘3d ausrichten’ to bring all trees to z=0.



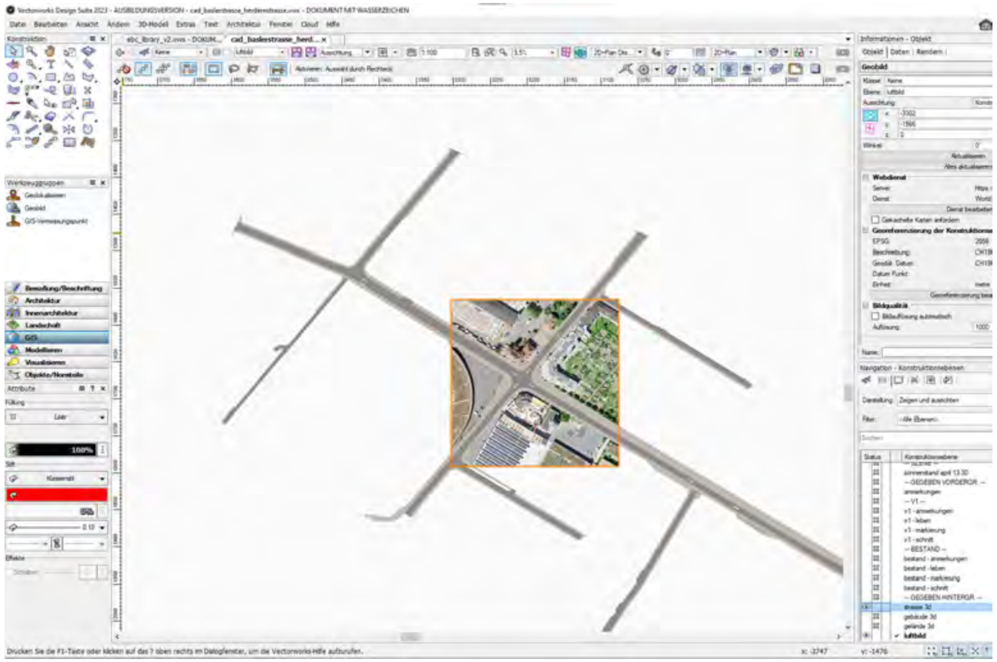
The result. Remove the 3d point you added before.

creating_scenes_in_vectorworks .01 lba.docx

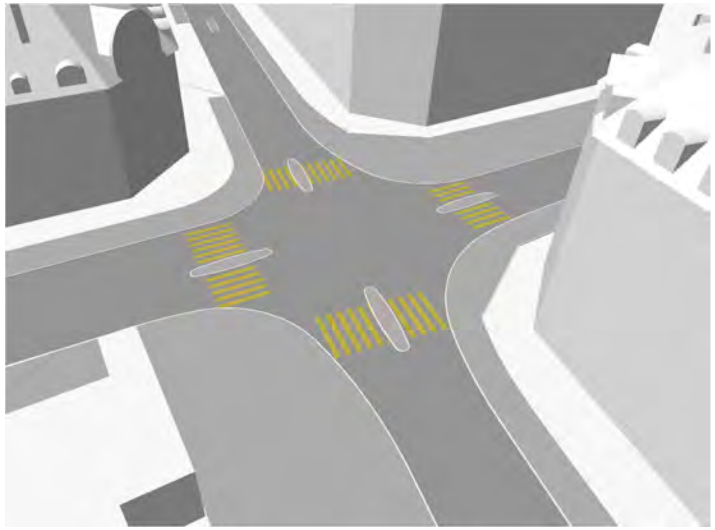


6. Adding existing road markings and details

Use the tool ‘Geobild’. Draw a rectangle in the area of interest. Change the resolution from ‘Bildauflösung automatisch’ to 1000. Make sure that it’s in the layer ‘Luftbild’.



Now, you can copy elements from an intersection in the library file and draw them over the aerial image



Chapter C: Appendix: MATSim process

MATSim simulations for the E-Bike City project – documentation

Aurore Sallard

Working paper **December 2024**

IVT Institut für Verkehrsplanung und Transportsysteme
Institute for Transport Planning and Systems

ETH
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

Contents

1 Overview

This document is thought to be a summary and documentation about the work I did for the E-Bike city project between June and December 2024. Most of this work involves working with MATSim, which is not known to be easy, so I made my best to be as precise as possible in describing the instructions required to make it work.

The most important github repository is located at: https://github.com/matsim-eth/e-bike-city. This is a public repository containing (almost) everything required to work with the redesigned street network, and run simulations and some analysis scripts. The most relevant branch is named `ebike_simulation_aurore`, it should be possible to focus on this one to run the most up-to-date simulations.

During my six months working on the project, I stored everything in the Euler server: `/cluster/work/ivt_vpl/asallard/EBC`. As I am now leaving the institute, this repository might be emptied/deleted at some point, so I backed up everything related to the EBC project in `/cluster/work/ivt_vpl/ebikecity/aurore`. The vast majority of this documentation was written refering to documents in `/cluster/work/ivt_vpl/asallard/EBC` but the architecture of the folder is the same in `/cluster/work/ivt_vpl/ebikecity/aurore` so it should be easy to adapt the required paths and find all the documents.

`/cluster/work/ivt_vpl/ebikecity` also contains some simulations backups created by Miriam Sonnak for her master thesis as well as all of the input data. It is not straightforward to understand directly how all steps are linked with each other from her report; I thus tried to be as explicit as possible in this document.

In order to run the simulations, Euler needs to understand how to compile the Java code and how to run it. There are two possibilities to do so:

- with Euler new software stack, one can directly import maven and a Java environment using the following lines:
  ```
  module load stack/2024-06
  module load gcc/12.2.0
  module load openjdk/17.0.8.1_1
  module load maven
  ```
- or we can set up our own Java and Maven repositories by installing Maven and a JDK locally in our own repository. For instance, I installed maven (version 3.9.9) and a JDK version 17.0.12 in my Euler personnal repository (`/cluster/work/ivt_vpl/asallard`) and imported the correct paths at the begining of each script involving Java:
  ```
  export PATH=/cluster/work/ivt_vpl/asallard/apache-maven-3.9.9/bin:$PATH
  export PATH=/cluster/work/ivt_vpl/asallard/jdk-17.0.12+7/bin:$PATH
  export JAVA_HOME=/cluster/work/ivt_vpl/asallard/jdk-17.0.12+7/.
  ```
  I focused on this solution while working on the E-Bike City project but the first one should work too.

When compiling the Java code with Maven, it is important to have it understand that the resulting jar file has to contain all imported dependencies. The corresponding command line thus looks like:
`mvn -f /path_to_the_pom_file -DskipTests=true -Pstandalone package`. In the `ebike_simulation_aurore`, the default `pom.xml` file integrates MATSim 13. The code was however updated to MATSim 15, to compile it with this MATSim version, one should use `pom_MATSim15.xml`.

The next sections will present how to run MATSim simulations for the E-Bike city project, from the conversion of the OSM networks redesigned by Lukas Ballo to the simulation itself and the analysis of the results. The last section presents the main results of the conducted simulations.

This documentation is not meant to be exhaustive. Most instructions on how to run the scripts, correctly generate the .jar files etc can be found directly in the .sh scripts referenced below.

2 Importing an OSM network into MATSim

OSM networks need to be processed to be used for MATSim simulations. Four steps are required; they are depicted in Figure 58 (page 104) in Miriam's master thesis. The three first ones will be explained here while the last one will be presented in subsection 3.4.

Two OSM networks can be used: one corresponding to the current roadspace allocation, one corresponding to the E-Bike City network. Both OSM files were generated by Lukas Ballo end of June 2024 and they are located at `cluster/work/ivt_vpl/asallard/EBC/1.0_Network_import/OSM_networks/2024_06_26_export`.

2.1 Converting the OSM network into a MATSim network

The Osm2MultimodalNetwork script from PT2MATSim (version 22.3) is used here. I think that Miriam modified something in the code and did not push it anywhere, because when I tried and downloaded PT2MATSim to run the scripts, I ran into some errors. Thus, I would suggest using the already compiled jar file located at `/cluster/work/ivt_vpl/asallard/EBC/Code/pt2matsim-22.3-shaded-bike-cost-renamed.jar`.

To run this script, a config file (usually named `osm_conv_config.xml`) is required. The path to the input OSM file must be provided as a parameter named `"osmFile"` in the config, as well as the path to the output `.xml.gz` network, named `"outputNetworkFile"`. Please note that this output network does not contain any information about the public transport network and is consequently not the one that will be used to run the MATSim simulations.

The config file defines default parameters for the different OSM link types (motorways, residential,...). For each road type, `"allowedTransportModes"` defines the modes that are routed in the network that can access the links. Underneath the road type definitions, subnetworks are created to allow for the easy addition of new transport modes. For instance, trucks and car passengers are allowed to drive on the same roads as cars and ebike and s-pedelecs use the same network as bikes.

Configuration example files are provided in `cluster/work/ivt_vpl/asallard/EBC/1.0_-Network_import/OSM_to_MATSim_configs`. They are named as `osm_conv_config_-<mode>_<network>.xml`, where:

- "mode" is either "nobike" (ie bike trips will be teleported, no bike network is built), "bike" (ie bike trips are routed), "ebike" (bikes and ebikes are modeled as separate modes, both are routed) and "spedelec" (bikes, ebikes and spedelecs are modeled as separate modes, all of them are routed).
- "network" is either "before" (in which case the OSM data corresponding to the network before roadspace reallocation is used) or "after" (in which case the EBC network is used).

The script named `cluster/work/ivt_vpl/asallard/EBC/1.0_Network_import/1.0.1_-osm_to_matsim.sh` is an example of how this step can be ran on Euler, and the corresponding outputs are stored in `cluster/work/ivt_vpl/asallard/EBC/1.0_Network_-import/Outputs/2024_12_05_Interm`.

2.2 Importing public transport schedules

This step is independent from the OSM networks and the specific simulation parameters, it can thus be run independently from the rest of the code. Here, the goal is to use the `Hafas2TransitSchedule` script from PT2MATSim to load the public transport schedules and vehicles and convert them into a MATSim-compatible format. The required HAFAS

data is located at `/cluster/work/ivt_vpl/ebikecity/inputdata/hafas`. Based on this input, the script creates two `.xml.gz` files: an intermediate transit schedule –that we will map onto the network in the next step– and a collection of transit vehicles.

Those outputs are stored in `cluster/work/ivt_vpl/asallard/EBC/1.0_Network_import/Outputs/PT`. If necessary, this step can be run again using the `cluster/work/ivt_vpl/asallard/EBC/1.0_Network_import/1.0.2_load_pt_schedule.sh` script. The required outputs are:

- the path where the HAFAS data is stored;
- the reference coordinate system, here epsg:2056;
- the output path to the transit schedule file;
- the output path to the transit vehicles file;
- the date to be considered while reading the HAFAS data. Here, we are using October 1st, 2018. By experience from other projects, modifying this to a more recent date often leads to major errors in the simulations so make sure not to change it!

2.3 Mapping the public transport lines onto the MATSim network

The next step consists in mapping the transformed public transport schedule onto the intermediate MATSim network. Once again, a script from PT2MATSim, `PublicTransitMapper`, will be used. This step is controlled by an `.xml` config file. Example config files are located in `cluster/work/ivt_vpl/asallard/EBC/1.0_Network_import/Mapper_configs`. Here are the parameters of interest:

- `inputNetworkFile`: path to the intermediate network created from the OSM input;
- `inputScheduleFile`: path to the intermediate transit schedule file created from the HAFAS data;
- `modesToKeepOnCleanUp`: the modes that are routed in the network. Specifically:
  - If all bike trips should be teleported, set this parameter to "car,car_passenger,truck".
  - If bike trips must be routed, set it to "car,car_passenger,truck,bike".
  - If ebikes are modeled, set it to "car,car_passenger,truck,bike,ebike".
  - If ebikes and spedelecs are modeled, set it to "car,car_passenger,truck,bike,ebike,spedelec".
- `outputNetworkFile`: path to the new network, now containing PT routes;
- `outputScheduleFile`: path to the mapped public transit schedule;
- `outputStreetNetworkFile`: I think this file is never used afterwards.

One can use the script named `cluster/work/ivt_vpl/asallard/EBC/1.0_Network_import/1.0.3_map_pt_to_network.sh` to run this step. The outputs are stored in `cluster/work/ivt_vpl/asallard/EBC/1.0_Network_import/Outputs/2024_12_05_New`.

3 Running a MATSim simulation

The previous section showed how to convert OSM data into a network usable in a MATSim simulation and how to integrate public transport schedules into it. At this stage, we thus have three "ingredients" required to run a MATSim simulation: a network, a PT schedule description file, and a PT vehicle collection. Some key ingredients are still missing: the population and its travel plans, the households, and the facilities (ie the locations where the agents' activities take place). This section will give an overview on the process that prepares this input for the simulation.

3.1 Input populations and facilities

Base populations representing the EBC inhabitants and commuters are available in the `ebikecity` Euler repository (`/cluster/work/ivt_vpl/ebikecity/ebc_bl`). Two populations are already created and stored there: `population_ebc_bl_100.xml.gz` (sample size of 100%) and `population_ebc_bl_10.xml.gz` (sample size of 10%). Those populations represent all agents (persons and freight) having at least one trip or one activity in the EBC study perimeter during an average working day. They were generated by Miriam and/or Milos from a complete Switzerland eqasim scenario, but the exact code that they used to cut out the required agents is nowhere to be found. The corresponding facility file is stored next to both populations, at `/cluster/work/ivt_vpl/ebikecity/ebc_bl/facilites_ebc_bl.xml.gz`.

3.2 Adapting the population size

To run smaller experiments, it often makes sense to test the code on a much smaller population because the EBC population is really really large (2.5 million agents). A script developed by Miriam (ebike_simulation branch –for instance– → utils → ReducedSample.java) allows to randomly select agents from an input population.

The script `2.0.1_reduce_sample.sh` in `/cluster/work/ivt_vpl/asallard/EBC/2.0_Simulation_setup` shows how to run that script. Four arguments are required:

- the path to the input (large) population;
- the network (corresponding to the population) – it is only read by the script and not modified, probably the script could work without it;
- the path to the output (smaller) population;
- the desired sample size – for instance 1.0 corresponds to a full-size population without downsampling, 0.01 to 1%.

3.3 Modifying population attributes

It is sometimes necessary to add new attributes to the population. For instance, the mode choice model estimated by Lucas Meier de Freitas requires to know the urbanization level at the agents' residence. This information is not included by default in the MATSim populations, it is thus necessary to impute it from other sources. Here, a detailed map of the urbanization level could have been used, but, to make the process faster and because reading spatial datasets in Java is often not straightforward, another solution was found. From the eqasim pipeline, a csv table linking each personal ID from STATPOP to an urbanization level (high, medium or low) was generated. It is stored in `/cluster/work/ivt_vpl/asallard/EBC/2.0_Simulation_setup/Statpop_urbanisation_level/statpop_spatial.csv`.

To connect the urbanization levels obtained from STATPOP to the MATSim population, one can use the ImputeDegUrba.java script (ebike_simulation branch → utils → ImputeDegUrba.java). Four arguments are required:

- the path to the original MATSim population;
- the path to the CSV table linking STATPOP ID and urbanization level;
- the path to the output population, with the new urbanization level attribute added;
- the path to a CSV file storing the population (optionnal, just comment out the last line to write the CSV).

The script `2.0.2_add_urbanization_lvl.sh` shows how to run the script.

In the `/cluster/work/ivt_vpl/asallard/EBC/2.0_Simulation_setup/Populations` folder, the following populations are stored:

- `population_ebc_bl_01.xml.gz`: created from the base ebc_bl population with a sampling size of 0.1%.
- `population_from_outputs_bike_teleported.xml.gz`: created from the outputs of the first MATSim simulation run after the update to MATSim15. This is a simulation with 100% sampling size, run on the network before reallocation, with no ebikes nor spedelecs and teleported bike trips. This simulation was run for 90 iterations and, following what Miriam did in her thesis, serves as a base for all following simulations, i.e. all simulations are run from the results of this one. More details will be given in section 6. Here, `population_from_outputs_bike_teleported.xml.gz` is only a copy of the generated `output_plans` file, but it will serve as a basis for all the other populations so I think it makes sense to copy it here.
- `population_from_outputs_bike_teleported_01.xml.gz`: a 0.1% sample of the previous population.
- `population_from_outputs_bike_teleported_urbalvl.xml.gz`: the full-size population, now with imputed urbanization level for each agent.
- `population_from_outputs_bike_teleported_01_urbalvl.xml.gz`: the full-size population, now with imputed urbanization level for each agent.

3.4 Mapping the population and the facilities onto the new network

Before we can start running a simulation, it is necessary to make sure that the population and the facilities are adapted to the new network. Miriam developed a Java code named `MapFacilities` (located in utils in the ebike_simulation branch among others) that adjusts the link IDs from which the facilities are accessible. The link IDs in the agents' plans are adjusted too. This script requires several arguments:

- the path to the old/reference network;
- the path to the reference population;
- the path to the reference facilities;
- the path to the intermediate network created in subsection 2.1;
- the path to the new population;
- the path to the new facilities.

It is only necessary to run this script once on the initial population, to ensure that the link IDs in the facilities and plans description match with those contained in the new OSM networks provided by Lukas Ballo. Afterwards, even if one switches between the network

before and after reallocation of road-space, the fact that the link IDs are consistent between those two networks allow one not to have to apply MapFacilities. However, as soon as a new network –with additional bike-like modes is introduced, or if we are switching between the networks before and after reallocation–, the following step is necessary.

For simulations where bike trips (and associated modes such as ebikes and spedelecs) are routed, a second code, `MapFacilitiesBike`, developed by Miriam too, is needed to make sure that all facilities are accessible for bikes. Please refer to the appendix of Miriam's thesis for more details about those two Java pieces of code. `MapFacilitiesBike` requires five arguments:

- the path to the new network created in subsection 2.3;
- the path to the reference population;
- the path to the reference facilities;
- the path to the new population;
- the path to the new facilities.

The script `2.0.3_map_population.sh` in `/cluster/work/ivt_vpl/asallard/EBC/2.0_Simulation_setup` shows how to apply this to the `population_from_outputs_bike_teleported.xml.gz` presented above.

The inputs required to run simulations with the two networks –before and after reallocation– and bike trips routed are already created and stored in `/cluster/work/ivt_vpl/asallard/EBC/2.0_Simulation_setup/Populations_mapped` and `Facilities_mapped`. Here is an overview of the existing files:

- `Populations_mapped/population_from_outputs_spedelec_before_mappedBike.xml.gz`: works with the network before reallocation, full-size population.
- `Populations_mapped/population_from_outputs_spedelec_before_mappedBike_01.xml.gz`: works with the network before reallocation, 0.1% population.
- `Populations_mapped/population_from_outputs_spedelec_after_mappedBike.xml.gz`: works with the network after reallocation, full-size population.
- `Populations_mapped/population_from_outputs_spedelec_after_mappedBike_01.xml.gz`: works with the network after reallocation, 0.1% population.
- `Facilities_mapped/population_from_outputs_spedelec_before_mappedBike.xml.gz`: works with the network before reallocation, full-size population.
- `Facilities_mapped/population_from_outputs_spedelec_before_mappedBike_01.xml.gz`: works with the network before reallocation, 0.1% population.

- `Facilities_mapped/population_from_outputs_spedelec_after_mappedBike.xml.gz`: works with the network after reallocation, full-size population.
- `Facilities_mapped/population_from_outputs_spedelec_after_mappedBike_01.xml.gz`: works with the network after reallocation, 0.1% population.

3.5 Running a MATSim simulation

All the required inputs for the MATSim simulation have now been generated, the only thing left to do is to start the simulation itself. While we previously created the "ingredients" required to run the simulation – road network, transit schedule, transit vehicles, population and facilities –, we now have to make sure that the "recipe", i.e. the MATSim configuration file is processing correctly the ingredients. Two configuration example files are given in `/cluster/work/ivt_vpl/asallard/EBC/2.1_Run_simulation`: one to work a simulation with the network before roadspace reallocation (`config_simulation_before.xml`) and one corresponding to a simulation with the reallocated road network (`config_simulation_after.xml`).

Before running a simulation, it is extremely important to check the following parameters in the configuration file:

- `outputDirectory`: where the simulation results and logs will be stored. It is advised to use the `scratch` domain from Euler as the count and size of the generated files can be massive, before copying only the required outputs to the working directory once the simulation is completed.
- `lastIteration`: the number of iterations to be performed.
- `inputPlansFile`: the path to the population's plans.
- `inputNetworkFile`: the path to the network that will be used in the simulation.
- `inputFacilitiesFile`: the path to the facilities file.
- `transitScheduleFile`: the path to the transit schedule.
- `vehiclesFile` in the `transit` module: the path to the transit vehicles.
- `flowCapacityFactor` in the `qsim` module: should be equal to the sample size chosen for the population.

There is actually a last "ingredient", never mentioned above, that is defined in the configuration file too: the household file. As the households do not need to be remapped when the network changes, it is possible to use the baseline households stored in `/cluster/work/ivt_vpl/ebikecity/ebc_new/households_ebc.xml.gz` and called, in

the configuration file, by the `inputFile` parameter from the `households` module. The two aforementioned configuration files allow to run a simulation with the maximum number of modes possible: car, car passenger, walk, PT, truck (for freight agents), outside (for the agents spending some time outside the EBC study perimeter), bike, ebike and spedelec. If simulations with less bike options have to be run, example configuration files are given in the "old" simulation results, in `/cluster/work/ivt_vpl/asallard/EBC/3.0_Results_ASTRAmcm`.

Example scripts launching the simulations are given in `/cluster/work/ivt_vpl/asallard/EBC/2.1_Run_simulation`, once again, one corresponds to the simulation before roadspace reallocation (`2.1.1_run_simulation_before.sh`) and one to the simulation after roadspace reallocation (`2.1.2_run_simulation_after.sh`). More details about the command that is run are given in `2.1.1_run_simulation_before.sh`, and details on how to switch between different simulation setups can also be found in Miriam's thesis.

If the results are generated in the `scratch` domain and need to be copied to a more convenient place, the scripts `2.1.3_copy_results_before.sh` and `2.1.4_copy_results_after.sh` can be used. Given the current results location and the target result folder, defined in the two first lines, all relevant outputs are copied to the target folder.

4 A new mode choice model

Two mode choice models were used in the MATSim simulations conducted for the E-Bike City project. The "previous" model refers to the one estimated by Sebastian Hörl and Felix Becker in Hörl *et al.* (2021). The "new" one refers to the model estimated in Summer-Autumn 2024 by Lucas Meier de Freitas and that I calibrated in November 2024. Miriam has only worked with the previous model. For the TRB paper written in July 2024 with Lukas Ballo about accessibility, the previous model was the only one used too. The new mode choice model could only be employed in simulations from December 2024.

Details about the two mode choice models are given in Appendix A. There, you can find the equations describing the utility associated with each mode and the parameter values. An overview of the lasts steps of the calibration process are still located in `/cluster/work/ivt_vpl/asallard/EBC/0.4_calibration/2.0_calibration`.

In the following paragraphs of this section, we will see how the mode choice model was implemented. This will give hints on how to modify the pipeline if changes in the utility equations or the parameters must be implemented.

4.1 Adding s-pedelecs into the simulation

In our case, we want to add s-pedelecs as a new mode into the simulation.

Defining s-pedelecs: the new transport mode can be defined in the main simulation class, in our case, `RunEBCSimulation` in `project/mode_choice` (in the `ebike_simulation_aurore` branch). Miriam and Milos had already created the necessary structure to define ebikes. The new vehicle types are first added to the scenario admissible vehicle types with the `addVehicleType` function (see lines 119 to 124 in the Java script). Each new vehicle type is defined by its maximum velocity (25km/h for ebikes, 45km/h for s-pedelecs) and by the space it takes on the road compared to an individual car (0.25 both for ebikes and s-pedelecs). Afterwards (lines 217 to 242), a link travel time calculator is created and attached to the new "s-pedelec" mode.

Selecting agents having a s-pedelec: the populations do not contain any information on e-bike s-pedelec owners. We thus have to randomly select them among the agents having access to a bike. According to a mail sent by Lucas Meier de Freitas, in the 2021 Microcensus, 73.0% of bikes are usual bikes, 23.8% are e-bikes and 4.2% are s-pedelecs. Two config parameters are thus defined in `project/config/EBCConfigGroup`: `eBikeAvailability` and `spedelecAvailability`. These parameters appear line 118 and 119 in the config examples in `/cluster/work/ivt_vpl/asallard/EBC/2.1_RunSimulation`, in the `ebc` config module.

These parameters are then used in the `adjustBikeAvailability` function in `project/config/EBCConfigurator`. First, among all bike owners, a share of them is selected to be actually owning e-bikes. The `ebikeAvailability` parameter is thus set in the config to 0.238. Then, among the remaining bike owners, we select the s-pedelec owners. The `spedelecAvailability` parameter is thus set to $0.042 \div (1 - 0.238) = 0.0551$.

Please note that there is another similar parameter in the config: `bikeAvailability`. This parameter (set to 0.7 during the calibration) scales the bike ownership in the population before e-bike and s-pedelec owners are selected because it was observed that Microcensus

data tend to overestimate bike usage (probably because of all respondents who have bikes at home but never use it, or just for leisure).

Ensuring vehicle availability: this last step consists in ensuring that the vehicle type available to bike owning agents corresponds to the actual bike type they own. This is what is done in `project/mode_choice/EBCModeAvailability`: the agents selected as e-bike users loose their access to bikes and gain access to an e-bike, and the agents selected as s-pedelec users loose their access to bikes and gain access to a s-pedelec.

4.2 Implementing a new mode choice model

Computing the necessary variables: this step is quite difficult to explain as many variables are computed in the background. The main idea is the following: in `project/mode_choice/variables`, one can define variable classes, such as `EBCBikeVariables`, `EBCTripVariables`, `EBCPersonVariables` and `EBCPtVariables`. Those classes are only used to declare variables.

Their values are actually computed from predictors located in `project/mode_choice/predictors`: `EBCBikePredictor`, `EBCAccessEgressBikePredictor`, among others. This is where most of the variables are actually computed. Most of them are computed from imported classes, but for some others, the explicit computation is described in the predictors (see for instance the computation of the network distance or the parking duration in `EBCTripPredictor`). An auxiliary file, `EBCPredictorUtils`, helps accessing person-related variables.

Model parameters: the parameters resulting from the model estimation and calibration are given in `project/mode_choice/EBCModeParameters`. A first generic class of mode parameters, `EBCBaseModeParameters`, is created, it will define most of the mode-specific parameters. PT parameters usually look quite different so they are often defined in their own class, `EBCPtParameters` here. The `modeParamInclEBike` function (I took the name from Miriam) defines and returns the parameters themselves. Please note that the parameters given lines 47 to 52, under the "General" comment, are not used, they were just copied from a previous class.

Computing the utilities: the final utility computation takes place in an utility estimator, located in `project/mode_choice/estimators`. One estimator class is defined per mode (`EBCSpedelecUtilityEstimator`, `EBCWalkUtilityEstimator`, `EBCPtUtilityEstimator`...). Some modes, such as car passenger and truck (for freight vehicles), are fixed for the agents and cannot be changed during the re-planning stage of the MATSim iterations. For those, no utility computation is thus needed.

Each utility estimator is built according to the same structure: at the end of the code, the `estimateUtility` function calls the required variables. Each component of the utility is then computed from specific functions defined above (`estimateConstantUtility`, `estimateTravelTimeUtility`, ...) and added to the returned utility value.

Binding utility estimators: finally, we have to make sure that the utility estimators are used for the correct modes during the simulation. This is what is done in the `installEqasimExtension` in `project/mode_choice/EBCModule`. We also have to ensure that the correct classes are called by the config, especially in the `eqasim` config module, where the names of the utility estimators must be defined for each mode.

5 Analysis

5.1 Inputs for Lukas Ballo's accessibility computations

For the accessibility paper we worked on in Summer 2024 with Lukas Ballo, he needed to have access to average travel times by link and mode at various times of the day and vehicle counts, once again at different times of the day. A Java script was created to compute all of this data. This script is `utils/AnalysisTravelTimeFromEvents`, in the `ebike_simulation_aurore` branch of the EBC github repository. This script takes as inputs (in this sequence) the path to the events that must be analyzed, the path to the output CSV file where the results will be created and the path to the network used in the simulation. An example script on how to run this code can be found in `/cluster/work/ivt_vpl/asallard/EBC/4.0_Analysis_TravelTimes/4.0.0_computeTTfromevents.sh`.

The output CSV has the following columns:

- LinkId: link ID in the MATSim network
- OSM_ID: the link ID in the original OSM network
- FreeflowTTCar: minimal link travel time by car
- FreeflowTTBike: minimal link travel time by bike
- for each time bin of the format HH:MM – "0:00" is the time bin from 00:00 to 00:30; "0:30" the time bin from 00:30 to 01:00 etc.
  - car_HH:MM: the average travel time for cars on this link in the corresponding time bin. If no car traveled on the link during the time bin, the value is NA.
  - N_cars_HH:MM: the number of cars that have traveled on that link during the time bin.
  - bike_HH:MM: the average travel time for bikes on this link in the corresponding time bin. If no bike traveled on the link during the time bin, the value is NA.
  - N_bikes_HH:MM: the number of bike that have traveled on that link during the time bin.

The Java script will probably need to be adapted to consider ebikes and s-pedelecs separately from normal bikes. The necessary updates will then have to be made in `utils/AnalysisTravelTimeEventsHandler`, the events handler class called by `utils/AnalysisTravelTimeFromEvents`.

5.2 Mode share analysis (from the mode choice model calibration)

For this analysis, a Python code was implemented. It compares the mode shares computed at the end of a MATSim simulation to 2021 Microcensus reference values provided by Lucas Meier de Freitas. The code is stored here: https://github.com/AuroreSallard/ebc_modeshare_analysis.

As it is a Python code calling external libraries, it makes sense to create an environment specific to this project. A script describing how to do this is given in `/cluster/work/ivt_vpl/asallard/EBC/5.0_ModeShareAnalysis/create_environment.sh`. This script creates an environment at a location defined line 8, activates this environment and installs all required packages.

Once the environment is created, the analysis code itself can be run using the `/cluster/work/ivt_vpl/asallard/EBC/5.0_ModeShareAnalysis/5.0.0_run_analysis.sh` script. It requires 6 arguments:

- the path to the MATSim legs
- the path to the MATSim trips. Please note that we are using here the files created at the end of the last MATSim iteration (for instance, the legs and trips paths should look like `path_to_MATSim_results/ITERS/it.60/60.legs.csv.gz` and `path_to_MATSim_results/ITERS/it.60/60.trips.csv.gz`). The actual output results (whose paths should look like `path_to_MATSim_results/output_legs.csv.gz`) contain the same information, but the columns are named differently.
- path to the CSV with the reference mode share by distance computed from microcensus stages
- path to the CSV with the reference mode share by distance computed from microcensus trips
- path to the output folder where all the results will be stored
- path to a shapefile of the E-Bike city study perimeter –it is necessary beacuse the analysis script starts by filtering out all trips not taking place exclusively within this perimeter–.

The following outputs are created:

- Two CSV files copying the useful information from the MATSim legs and trips, because it takes time to read and process them, and especially to filter out trips or legs coming from or going outside the study perimeter.
- Three figures showing:
  - An aggregated comparison of the mode share by trips, comparing MATSim results with the Microcensus reference values.
  - A comparison of mode share by traveled distance (5km bins up to 70km) comparing MATSim results with Microcensus reference values, at the trips level.
  - Same, but at the stages/legs level.

6 Overview of the existing results

6.1 Previous mode choice model

This first set of results was generated in early October 2024 after the update to MATSim 15 was performed. They are located in `/cluster/work/ivt_vpl/asallard/EBC/3.0_Results_ASTRAmcm`. For this set of simulations, I followed Miriam's approach: a first baseline simulation was run with teleported bike trips and 90 iterations on the network before reallocation. Afterwards, the result plans coming from this baseline simulation were used as inputs for the next simulations, with routed bike trips, on both networks.

Bike teleportation simulation: this is the baseline simulation mentioned above. The results are stored in `MATSim15_bike_teleportation/outputs_100pct`. The e-bikes are not modeled here and the bike trips are teleported. This simulation was 90 iterations long. This ensures that a first baseline equilibrium is reached and that the modifications observed in the following simulations come from the implemented changes in the setup.

MATSim_bike simulations: the results are stored in `MATSim_15_bike_before/Outputs_100pct` for the network before road-space reallocation and `MATSim_15_bike_after/Outputs_100pct` for the redesigned E-Bike City network. The scripts `MATSim_15_bike_before/runSimulation_before.sh` and `MATSim_15_bike_after/runSimulation_after.sh` show how the population and facilities input files were created from the outputs of the baseline simulation: one has to apply the MapFacilitiesBike (subsection 3.4) script to 1. the `output_plans.xml.gz` output in `MATSim15_bike_teleportation/outputs_100pct` and the a file with the facilities mapped to the new network. It is not necessary to apply MapFacilities as the link IDs were already mapped in order to create the inputs of the baseline simulation; here, it is enough to add bike accessibility information to the facilities and the plans. Moreover, once again, because the link IDs are the same between the networks before and after reallocation, as long as the correct network is used by MapFacilitiesBike, the same process can be applied to create inputs for both networks. In each folder, the mapped population and facilities are located in a sub-folder named `Mapping`. Those files are used to run the simulations, this time for 60 iterations, as a first equilibrium has already been reached.

Compared to before, the bike trips are now routed into the network, and not simply teleported to their destination. Cyclists and drivers thus interact on the road, which has to be reflected in the config: in the `qsim` module, seepage is allowed for the bike mode to model the fact that cyclists are navigating from back to front in car queues. There are quite a lot of other changes in the config files that are required to model routed bike trips, it will be too long to go through all of them here so, if you want to see them, please compare the config in the baseline simulation folder with the one in a bike simulation.

MATSim_ebike simulations: the results are stored in MATSim_15_ebike_before/Outputs_100pct for the network before road-space reallocation and MATSim_15_ebike_after/Outputs_100pct for the redesigned E-Bike City network. The scripts MATSim_15_ebike_before/runSimulation_before.sh and MATSim_15_ebike_after/runSimulation_after.sh show how the population and facilities input files were created from the outputs of the baseline simulation before the simulation starts. The process is exactly the same as for the previous "bike" simulations. The only difference here is that e-bikes are now modeled into the simulation as fast bikes, although the utility function associated with both modes is the same. To achieve this, we had to use an e-bike network which explicitly allows the new e-bike mode to travel everywhere bikes are allowed. Once again, those simulations were run for 60 iterations.

Here, both bike and e-bike trips are routed into the network. Seepage is allowed for bikes and e-bikes. The corresponding results were shared with other groups in October 2024.

6.2 New mode choice model

This time, all modes, including e-bikes and s-pedelec were integrated directly into the simulation –there is no intermediate simulation with routed bikes but no e-bikes as with the previous mode choice model–. Two simulations were run, one for each network.

Once again, the input populations and facilities are obtained by mapping the outputs of the baseline simulations generated with the old mode choice model onto the networks adapted to the simulation setup (i.e., e-bikes and s-pedelecs are explicitly allowed on all paths where cyclists can drive). An additional step was necessary here as other attributes are required in the population to work with the new mode choice model. The process to include these additional attributes was described in subsection 3.3 The inputs for both simulations (before and after network road-space reallocation) are in /cluster/work/ivt_vpl/asallard/EBC/2.0_Simulation_setup/Populations_mapped and /cluster/work/ivt_vpl/asallard/EBC/2.0_Simulation_setup/Facilities_mapped. The results of those simulations –they were run for 60 iterations, with a higher re-planning rate of 0.1 compared to 0.05 before– are stored in /cluster/work/ivt_vpl/asallard/EBC/2.1_Run_simulation/Outputs_before for the network before reallocation and /cluster/work/ivt_vpl/asallard/EBC/2.1_Run_simulation/Outputs_after for the re-designed network.

These results were uploaded and shared on Polybox on December 13, 2024.

7 References

Hörl, S., F. Becker and K. W. Axhausen (2021) Simulation of price, customer behaviour and system impact for a cost-covering automated taxi system in zurich, *Transportation Research Part C: Emerging Technologies*, **123**, 102974, ISSN 0968-090X.

A Appendix: overview of the mode choice models

New mode choice model

Notes

Units:

- Agents' age: years
- Distance: km
- Durations / headway: hours!

Car utility

$$
\begin{aligned}
U_{\text{car}} = \; & \alpha_{\text{car}} \\
& + \beta_{\text{TT,car}} \; x_{\text{TT, car}} \\
& + \beta_{\text{parking cost}} \; x_{\text{parking cost}} \\
& + \beta_{\text{cost}} \; x_{\text{cost, car}} \\
& + \beta_{\text{externalities, car}} \; \gamma_{\text{externalities by km, car}} \; x_{\text{in-vehicle distance, car}}
\end{aligned}
$$

With:

- $\alpha_{\text{car}} = 0.3$[1]
- $\beta_{\text{TT,car}} =$ -6.0 hour^{-1}[2]
- $\beta_{\text{parking cost}} =$ -0.305164
- $\beta_{\text{cost}} =$ -0.06934
- $\beta_{\text{externalities, car}} = +0.644314$
- $\gamma_{\text{externalities by km, car}} = +0.1601$ km^{-1}

Cost models:

- Parking cost: 0 if the trip purpose is home or work. Otherwise, if the destination is within the city center, 4 CHF/hour; else, 2 CHF/hour.
- Trip cost: 0.188 CHF/km

[1]Before calibration: 0.0.
[2]Before calibration: -4.376983 hour^{-1}

PT utility

$$
\begin{aligned}
U_{\text{PT}} = \; & \alpha_{\text{PT}} \\
& + \beta_{\text{female, PT}} \; x_{\text{sex==female}} \\
& + \beta_{\text{age, PT}} \; x_{\text{age}} \\
& + \beta_{\text{degurba2, PT}} \; x_{\text{degurba==medium}} \\
& + \beta_{\text{degurba3, PT}} \; x_{\text{degurba==low}} \\
& + \beta_{\text{TT,PT}} \; x_{\text{TT, PT}} \\
& + \beta_{\text{access egress time, PT}} \; x_{\text{access egress time, PT}} \\
& + \beta_{\text{freq}} \; x_{\text{freq, PT}} \\
& + \beta_{\text{cost}} \; x_{\text{cost, PT}} \\
& + \beta_{\text{externalities, PT}} \; \gamma_{\text{externalities by km, PT}} \; x_{\text{in-vehicle distance, PT}}
\end{aligned}
$$

With:

- $\alpha_{\text{PT}} =$ -0.8[3]
- $\beta_{\text{female, PT}} = +0.31345$
- $\beta_{\text{age, PT}} = +0.00354$
- $\beta_{\text{degurba2, PT}} =$ -0.94476
- $\beta_{\text{degurba3, PT}} =$ -1.25242
- $\beta_{\text{TT,PT}} =$ -2.0 hour^{-1}[4]
- $\beta_{\text{access egress time, PT}} =$ -1.96973 hour^{-1}
- $\beta_{\text{freq}} =$ -0.50346 hour^{-1}
- $\beta_{\text{cost}} =$ -0.06934
- $\beta_{\text{externalities, PT}} = +1.44709$
- $\gamma_{\text{externalities by km, PT}} = +0.08$ km^{-1}.

Cost model:

- Trip cost: $x_{\text{cost, PT}} = (\delta_{\text{hasAbo}} \times \frac{1}{2}) \times \max(3.4, \delta_{\text{pt\_dist} \leqslant 5\text{km}} \times 0.89 \times x_{\text{pt\_dist}} + \delta_{\text{pt\_dist} \geqslant 5\text{km}} \times$

[3]Before calibration: -1.34541
[4]Before calibration: -3.21258 hour^{-1}

$0.589 x_{\text{pt\_dist}})$

Bike utility

$$U_{\text{bike}} = \alpha_{\text{bike}}$$
$$+ \beta_{\text{female, bike}}\ x_{\text{sex==female}}$$
$$+ \beta_{\text{age, bike}}\ x_{\text{age}}$$
$$+ \beta_{\text{degurba2, bike}}\ x_{\text{degurba==medium}}$$
$$+ \beta_{\text{degurba3, bike}}\ x_{\text{degurba==low}}$$
$$+ \beta_{\text{TT,bike}}\ x_{\text{TT, bike}}$$
$$+ \beta_{\text{cost}}\ x_{\text{cost, bike}}$$
$$+ \beta_{\text{externalities, bike}}\ \gamma_{\text{externalities by km, bike}}\ x_{\text{distance, bike}}$$

With:

- $\alpha_{\text{bike}} = 1.4$ [5]
- $\beta_{\text{female, bike}} = -0.03147$
- $\beta_{\text{age, bike}} = -0.02074$
- $\beta_{\text{degurba2, bike}} = -1.29194$
- $\beta_{\text{degurba3, bike}} = -1.92303$
- $\beta_{\text{TT,bike}} = -2.4$ hour^{-1}[6]
- $\beta_{\text{cost}} = -0.06934$
- $\beta_{\text{externalities, bike}} = +3.18593$
- $\gamma_{\text{externalities by km, bike}} = -0.0364$ km^{-1}

Cost model:

- Trip cost: 0

[5]Before calibration: 1.22846
[6]Before calibration: -3.68053 hour^{-1}

MATSim simulations for the EBC Project December 2024

E-Bike utility

$$U_{\text{ebike}} = \alpha_{\text{ebike}}$$
$$+ \beta_{\text{female, ebike}}\ x_{\text{sex==female}}$$
$$+ \beta_{\text{age, ebike}}\ x_{\text{age}}$$
$$+ \beta_{\text{degurba2, ebike}}\ x_{\text{degurba==medium}}$$
$$+ \beta_{\text{degurba3, ebike}}\ x_{\text{degurba==low}}$$
$$+ \beta_{\text{TT,ebike}}\ x_{\text{TT, ebike}}$$
$$+ \beta_{\text{cost}}\ x_{\text{cost, ebike}}$$
$$+ \beta_{\text{externalities, ebike}}\ \gamma_{\text{externalities by km, ebike}}\ x_{\text{distance, ebike}}$$

With:

- $\alpha_{\text{ebike}} = -0.8$[7]
- $\beta_{\text{female, ebike}} = +0.32921$
- $\beta_{\text{age, ebike}} = +0.00268$
- $\beta_{\text{degurba2, ebike}} = -0.51416$
- $\beta_{\text{degurba3, ebike}} = -0.64266$
- $\beta_{\text{TT,ebike}} = -2.0$ hour^{-1} [8]
- $\beta_{\text{cost}} = -0.06934$
- $\beta_{\text{externalities, ebike}} = 0$
- $\gamma_{\text{externalities by km, ebike}} = +0.0264$ km^{-1} (but not relevant because $\beta_{\text{externalities, ebike}} = 0$).

Cost model:

- Trip cost: 0

[7]Before calibration: -1.64421
[8]Before calibration: -2.78651 hour^{-1}

Spedelec utility

$$U_{\text{Spedelec}} = \alpha_{\text{Spedelec}} + \beta_{\text{female, Spedelec}}\, x_{\text{sex==female}} + \beta_{\text{age, Spedelec}}\, x_{\text{age}} + \beta_{\text{degurba2, Spedelec}}\, x_{\text{degurba==medium}} + \beta_{\text{degurba3, Spedelec}}\, x_{\text{degurba==low}} + \beta_{\text{TT,Spedelec}}\, x_{\text{TT, Spedelec}} + \beta_{\text{cost}}\, x_{\text{cost, Spedelec}} + \beta_{\text{externalities, Spedelec}}\, \gamma_{\text{externalities by km, Spedelec}}\, x_{\text{distance, Spedelec}}$$

With:

- $\alpha_{\text{Spedelec}} = -1.4$[9]
- $\beta_{\text{female, Spedelec}} = -0.363751$
- $\beta_{\text{age, Spedelec}} = -0.026566$
- $\beta_{\text{degurba2, Spedelec}} = -0.464518$
- $\beta_{\text{degurba3, Spedelec}} = -0.651147$
- $\beta_{\text{TT,Spedelec}} = -0.3\ \text{hour}^{-1}$[10]
- $\beta_{\text{cost}} = -0.06934$
- $\beta_{\text{externalities, Spedelec}} = 0$
- $\gamma_{\text{externalities by km, Spedelec}} = +0.0264\ \text{km}^{-1}$ (but not relevant because $\beta_{\text{externalities, Spedelec}} = 0$).

Cost model:

- Trip cost: 0

[9]Before calibration: -2.550656
[10]Before calibration: -0.774801 hour^{-1}

MATSim simulations for the EBC Project December 2024

Walk utility

$$U_{\text{walk}} = \alpha_{\text{walk}} + \beta_{\text{female, walk}}\, x_{\text{sex==female}} + \beta_{\text{age, walk}}\, x_{\text{age}} + \beta_{\text{degurba2, walk}}\, x_{\text{degurba==medium}} + \beta_{\text{degurba3, walk}}\, x_{\text{degurba==low}} + \beta_{\text{TT,walk}}\, x_{\text{TT, walk}} + \beta_{\text{cost}}\, x_{\text{cost, walk}} + \beta_{\text{externalities, walk}}\, \gamma_{\text{externalities by km, walk}}\, x_{\text{distance, walk}}$$

With:

- $\alpha_{\text{walk}} = 0.8$[11]
- $\beta_{\text{female, walk}} = +0.07087$
- $\beta_{\text{age, walk}} = -0.00447$
- $\beta_{\text{degurba2, walk}} = -0.70167$
- $\beta_{\text{degurba3, walk}} = -0.37095$
- $\beta_{\text{TT,walk}} = -2.0\ \text{hour}^{-1}$ [12]
- $\beta_{\text{cost}} = -0.06934$
- $\beta_{\text{externalities, walk}} = 0.0$[13]
- $\gamma_{\text{externalities by km, walk}} = -0.0997\ \text{km}^{-1}$.

Cost model:

- Trip cost: 0

[11]Before calibration: +1.91847
[12]Before calibration: -5.52097 hour^{-1}
[13]Before calibration: +13.6768

Previous model

Car utility

$$
\begin{aligned}
U_{\text{car}} = \;& \alpha_{\text{car}} \\
& + \beta_{\text{TT,car}}\; x_{\text{IVT}} \left(\frac{x_{\text{dist}}}{\mu_{\text{dist}}}\right)^{\lambda_{\text{distTT}}} \\
& + \beta_{\text{TT,walk}}\; x_{\text{AET}} \\
& + \beta_{\text{cost}} \left(\frac{x_{\text{dist}}}{\mu_{\text{dist}}}\right)^{\lambda_{\text{dist cost}}} x_{\text{cost}} \left(\frac{x_{\text{hhIncome}}}{\mu_{\text{hhIncome}}}\right)^{\lambda_{\text{hhIncome}}} \\
& + \beta_{\text{work, car}}\; \chi_{\text{work}} \\
& + \beta_{\text{city center,car}}\; \chi_{\text{city center}}
\end{aligned}
$$

Variables:

- x_{IVT}: in-vehicle time (min)
- x_{dist}: euclidean distance (km)
- x_{AET}: access-egress time (min)
- x_{cost}: cost of the trip (CHF) (computed from a linear equation* linking the cost of the car trip with the travelled distance: cost = 0.26 [CHF/km]$\times$ in vehicle distance in km)
- x_{hhIncome}: the agent's household income (CHF)
- χ_{work}: true if the origin or destination purpose is work, false otherwise (-)
- $\chi_{\text{city center}}$: true if the origin or the destination of the trip lies within the boundaries of the city of Zurich, false otherwise (-)

Parameters:

- α_{car}: -0.8 (CHF)
- $\beta_{\text{TT, car}}$: -0.0192 (CHF/min)
- μ_{dist}: 39.0 km (reference distance)
- λ_{distTT}: 0.1147 (elasticity between travel time and distance)
- $\beta_{\text{TT, walk}}$: -0.0457 (CHF/min)
- β_{cost}: -0.088 (-)
- μ_{hhIncome}: 12260 CHF (reference household income)
- $\lambda_{\text{dist cost}}$: -0.2209 (elasticity between travel cost and distance)

- $\lambda_{\text{hhIncome}}$: -0.8169 (elasticity between cost and household income)
- $\beta_{\text{work, car}}$: -1.1606 (CHF)
- $\beta_{\text{city center, car}}$: -0.4590 (CHF)

PT utility

There are 8 components: constant, in-vehicle travel time utility, access egress utility, waiting time utility, line switches utility, monetary cost utility, headway utility, OVGK utility.

$$
\begin{aligned}
U_{\text{PT}} = \;& \alpha_{\text{PT}} \\
& + (\beta_{\text{railTT}}\; x_{\text{railTT}} + \beta_{\text{busTT}}\; x_{\text{busTT}}) \left(\frac{x_{\text{dist}}}{\mu_{\text{dist}}}\right)^{\lambda_{\text{distTT}}} \\
& + \beta_{\text{AET}}\; x_{\text{AET}} \\
& + \beta_{\text{wait}}\; x_{\text{waiting time}} \\
& + \beta_{\text{lineSwitch}}\; x_{\text{number of connections}} \\
& + \beta_{\text{cost}} \left(\frac{x_{\text{dist}}}{\mu_{\text{dist}}}\right)^{\lambda_{\text{dist cost}}} x_{\text{cost}} \left(\frac{x_{\text{hhIncome}}}{\mu_{\text{hhIncome}}}\right)^{\lambda_{\text{hhIncome}}} \\
& + \beta_{\text{headway}}\; x_{\text{headway}} \\
& + \beta_{\text{OVGK}}
\end{aligned}
$$

Variables:

- $x_{\text{rail TT}}$: rail travel time (min)
- $x_{\text{bus TT}}$: bus travel time (min)
- x_{dist}: euclidean distance (km)
- x_{AET}: access-egress time (min)
- $x_{\text{waiting time}}$: waiting time (min)
- $x_{\text{number of connections}}$: number of connections (-)
- x_{cost}: cost of the trip (CHF), see below
- x_{hhIncome}: the agent's household income (CHF)
- x_{headway}: interval between two vehicles (seconds?)

Parameters:

- α_{PT}: 0.0 (CHF, reference)
- β_{railTT}: -0.0072 (CHF/min)
- β_{busTT}: -0.0124 (CHF/min)
- μ_{dist}: 39.0 km (reference distance)
- λ_{distTT}: 0.1147 (elasticity between travel time and distance)
- β_{AET}: -0.0142 (CHF/min)
- β_{wait}: -0.0124 (CHF/min)
- $\beta_{\text{lineSwitch}}$: -0.17 (CHF) (not sure about the value)
- β_{cost}: -0.088 (-)
- μ_{hhIncome}: 12260 CHF (reference household income)
- $\lambda_{\text{dist cost}}$: -0.2209 (elasticity between travel cost and distance)
- $\lambda_{\text{hhIncome}}$: -0.8169 (elasticity between cost and household income)
- β_{headway}: -0.0301 (CHF/sec) (not sure about the unit)
- β_{OVGK}: penalty or reward associated with each PT "Güteklasse": 0 if OVGK class A, -1.7436 if OVGK class B, -1.6413 if OVGK class C, -0.9649 if OVGK class D, -1.0889 if OVGK class None.

Notes:

- When computing the travel time utility equation*, if both $x_{\text{rail TT}}$ and $x_{\text{bus TT}}$ are strictly greater than 0, the utility becomes

$$\beta_{railTT} x_{\text{rail TT}} \left(\frac{x_{\text{dist}}}{\mu_{\text{dist}}}\right)^{\lambda_{\text{distTT}}} + \beta_{\text{feeder TT}} x_{\text{bus TT}}$$

  with $\beta_{\text{feeder TT}} = -0.0452$ CHF/min. This means that the bus travel time is weighted by a different parameter and the distance doesn't play a role, the bus service is only considered as a feeder to the rail service.
- PT cost computation:
  - cost per km: 0.6 CHF/km
  - if the agent owns a GA, the cost is 0.
  - if the agent owns a regional subscription and the trips takes place within a radius of 15km around the agent's residence, the cost is 0.
  - if the agent owns a Halbtax subscription, half of the cost (cost per km * distance) is returned
  - in all other cases, the full cost is returned. We make sure that a minimum amount of money (2.7 CHF) is paid to avoid ridiculously small prices.

Bike utility

Fortunately there are only three components: constant, travel time and age.

$$\begin{aligned} U_{\text{PT}} = \quad & \alpha_{\text{bike}} \\ & + \beta_{\text{TT, bike}}\, x_{\text{bike, TT}} \left(\frac{x_{\text{dist}}}{\mu_{\text{dist}}}\right)^{\lambda_{\text{distTT}}} \\ & + \beta_{\text{age} \geq 60\text{, bike}}\, \chi_{\text{age} \geq 60} \end{aligned}$$

Variables:

- $x_{\text{bike TT}}$: bike travel time (min)
- x_{dist}: euclidean distance (km)
- $\chi_{\text{age} \geq 60}$: true if the agent is 60 years old or more, false else.

Parameters:

- α_{bike}: 0.1522 (CHF, reference)
- $\beta_{\text{TT, bike}}$: -0.1258 (CHF/min)
- μ_{dist}: 39.0 km (reference distance)
- λ_{distTT}: 0.1147 (elasticity between travel time and distance)
- $\beta_{\text{age} \geq 60\text{, bike}}$: -2.6588 (CHF)

Walk utility

There are three components: constant, travel time and penalty.

$$\begin{aligned} U_{\text{walk}} = \quad & \alpha_{\text{walk}} \\ & + \beta_{\text{TT, walk}}\, x_{\text{walk, TT}} \left(\frac{x_{\text{dist}}}{\mu_{\text{dist}}}\right)^{\lambda_{\text{distTT}}} \\ & + \left(1 - 100^{\frac{x_{\text{walk, TT}}}{\theta_{\text{threshold walk travel time}}}}\right) \end{aligned}$$

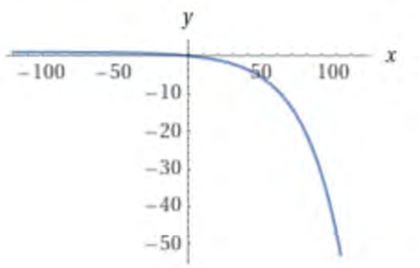
Variables:

- $x_{\text{walk TT}}$: walk travel time (min)
- x_{dist}: euclidean distance (km)

Parameters:

- α_{walk}: 0.5903 (CHF, reference)
- $\beta_{\text{TT, walk}}$: -0.0457 (CHF/min)
- μ_{dist}: 39.0 km (reference distance)
- λ_{distTT}: 0.1147 (elasticity between travel time and distance)
- $\theta_{\text{threshold walk travel time}}$: 120 (minutes)

Note: the last term corresponds to a penalty imposed to make sure that the walk travel times do not exceed a certain duration. Nothing is reported about how this penalty was computed and calibrated. The resulting penalty is depicted below:



Chapter D: Appendix: Further Simulation and Accessibility Results

Table D.1: Mean logsum accessibility changes, 7:00-7:30

		Entire Region excl. City of Zurich							City of Zurich							
		Age			Nationality		Sex		Age			Nationality		Sex		
State	Mode	Other	≤25	≥60	Other	Swiss	Female	Male	Other	≤25	≥60	Other	Swiss	Female	Male	All
Sample		110'025	59'412	50'430	70'249	149'618	109'890	109'977	46'197	20'125	15'451	24'423	57'350	40'917	40'856	304'474
Before	Cars	-inf	-inf	-inf	-inf	12.246	-inf	-inf	-inf	-inf	-inf	-inf	12.144	-inf	-inf	-inf
	PT	11.044	10.917	11.157	10.961	11.071	11.202	10.869	10.952	10.814	11.041	10.870	10.962	11.091	10.778	11.011
	Cycling	9.603	10.200	8.939	9.928	9.464	9.574	9.650	11.304	11.806	10.543	11.550	11.171	11.234	11.334	10.071
	Pedelec	11.143	11.058	11.221	11.094	11.158	11.302	10.973	11.786	11.698	11.881	11.738	11.801	11.948	11.617	11.314
	S-Pedelec	10.279	11.071	9.475	10.722	10.114	10.103	10.514	10.459	11.170	9.539	10.823	10.306	10.243	10.678	10.349
	Foot	8.260	8.344	8.036	8.277	8.210	8.258	8.205	11.087	11.052	10.769	11.033	11.012	11.030	11.006	9.002
After	Cars	-inf	-inf	-inf	-inf	12.058	-inf	-inf	-inf	-inf	-inf	-inf	11.670	-inf	-inf	-inf
	PT	11.044	10.917	11.157	10.961	11.071	11.202	10.869	10.952	10.814	11.041	10.870	10.962	11.091	10.778	11.011
	Cycling	9.740	10.337	9.076	10.065	9.600	9.711	9.787	11.530	12.044	10.787	11.785	11.402	11.468	11.564	10.234
	Pedelec	11.224	11.139	11.301	11.175	11.239	11.383	11.054	11.878	11.794	11.980	11.834	11.895	12.043	11.710	11.398
	S-Pedelec	10.295	11.087	9.491	10.738	10.130	10.119	10.530	10.474	11.186	9.555	10.839	10.321	10.259	10.693	10.365
	Foot	8.260	8.344	8.036	8.277	8.210	8.258	8.205	11.087	11.052	10.769	11.033	11.012	11.030	11.006	9.002
Diff	Cars[a]	-0.189	-0.187	-0.187	-	-0.188	-0.188	-0.187	-0.474	-0.462	-0.481	-	-0.474	-0.478	-0.471	-0.272
	PT	-0.000	-0.000	-0.000	-0.000	-0.000	-0.000	-0.000	-0.000	-0.000	-0.000	-0.000	-0.000	-0.000	-0.000	-0.000
	Cycling	+0.137	+0.137	+0.137	+0.137	+0.137	+0.137	+0.137	+0.226	+0.238	+0.244	+0.235	+0.231	+0.234	+0.230	+0.163
	Pedelec	+0.081	+0.081	+0.081	+0.081	+0.081	+0.081	+0.081	+0.092	+0.096	+0.098	+0.095	+0.094	+0.095	+0.093	+0.084
	S-Pedelec	+0.016	+0.016	+0.016	+0.016	+0.016	+0.016	+0.016	+0.015	+0.016	+0.016	+0.016	+0.015	+0.016	+0.015	+0.016
	Foot	-0.000	-0.000	-0.000	-0.000	-0.000	-0.000	-0.000	-0.000	-0.000	-0.000	-0.000	-0.000	-0.000	-0.000	-0.000
Before	All	12.868	12.620	12.823	12.376	12.985	12.844	12.737	13.197	13.150	13.052	12.957	13.244	13.198	13.118	12.892
After	All	12.830	12.644	12.783	12.426	12.930	12.826	12.712	13.161	13.210	12.997	13.053	13.180	13.185	13.099	12.872
Diff	All	-0.038	+0.024	-0.041	+0.050	-0.055	-0.019	-0.025	-0.036	+0.060	-0.055	+0.096	-0.064	-0.013	-0.019	-0.020

[a] Difference in car accessibility includes only individuals with a driver's license

Table D.2: Mean logsum accessibility changes for Seefeld, 7:00-7:30

		Seefeld						
		Age			Nationality		Sex	
State	Mode	Other	≤25	≥60	Other	Swiss	Female	Male
Sample		1'298	415	420	593	1'540	1'107	1'026
Before	Cars	-inf	-inf	-inf	-inf	11.920	-inf	-inf
	PT	11.240	11.149	11.358	11.192	11.267	11.396	11.084
	Cycling	11.307	11.883	10.635	11.554	11.183	11.258	11.317
	Pedelec	11.782	11.713	11.881	11.749	11.803	11.947	11.616
	S-Pedelec	10.433	11.167	9.568	10.753	10.272	10.217	10.610
	Foot	11.357	11.481	11.203	11.402	11.331	11.379	11.320
After	Cars	-inf	-inf	-inf	-inf	10.936	-inf	-inf
	PT	11.240	11.149	11.358	11.192	11.267	11.396	11.084
	Cycling	11.562	12.137	10.895	11.810	11.440	11.515	11.572
	Pedelec	11.894	11.825	11.994	11.862	11.915	12.060	11.728
	S-Pedelec	10.450	11.184	9.585	10.771	10.289	10.234	10.627
	Foot	11.357	11.481	11.203	11.402	11.331	11.379	11.320
Diff	Cars[a]	-0.988	-0.976	-0.974	-	-0.984	-0.980	-0.988
	PT	0.000	0.000	0.000	0.000	0.000	0.000	0.000
	Cycling	+0.256	+0.254	+0.260	+0.256	+0.256	+0.257	+0.255
	Pedelec	+0.112	+0.112	+0.114	+0.112	+0.112	+0.113	+0.112
	S-Pedelec	+0.017	+0.017	+0.017	+0.017	+0.017	+0.017	+0.017
	Foot	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Before	All	13.186	13.229	13.092	13.035	13.230	13.227	13.121
After	All	13.123	13.284	12.997	13.135	13.127	13.186	13.068
Diff	All	-0.063	+0.056	-0.094	+0.100	-0.103	-0.040	-0.053

a Difference in car accessibility includes only individuals with a driver's license

Figure D.1: Flows of motorized traffic - difference, 10:00-10:30

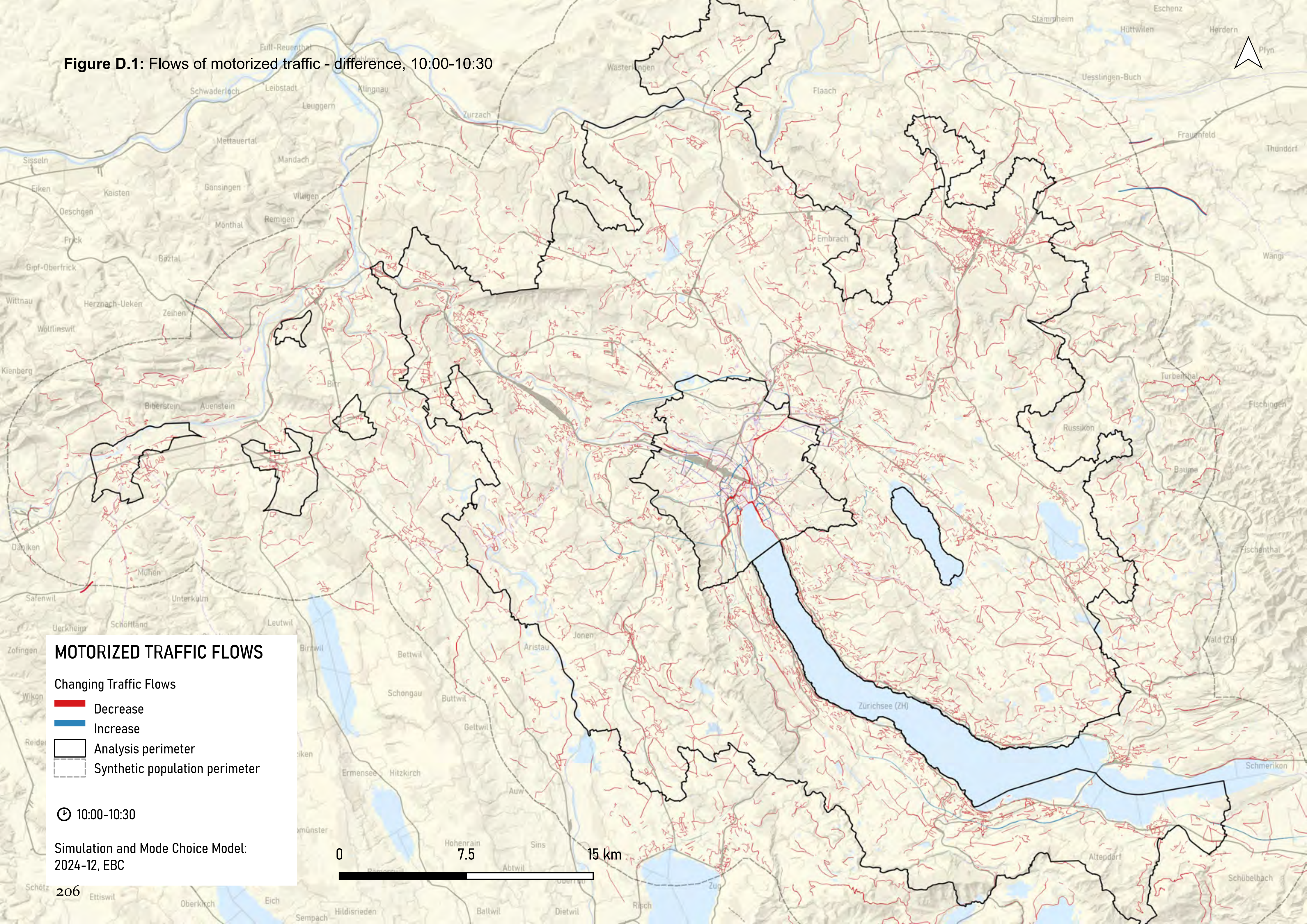


Figure D.2: Flows of motorized traffic - before, 10:00-10:30

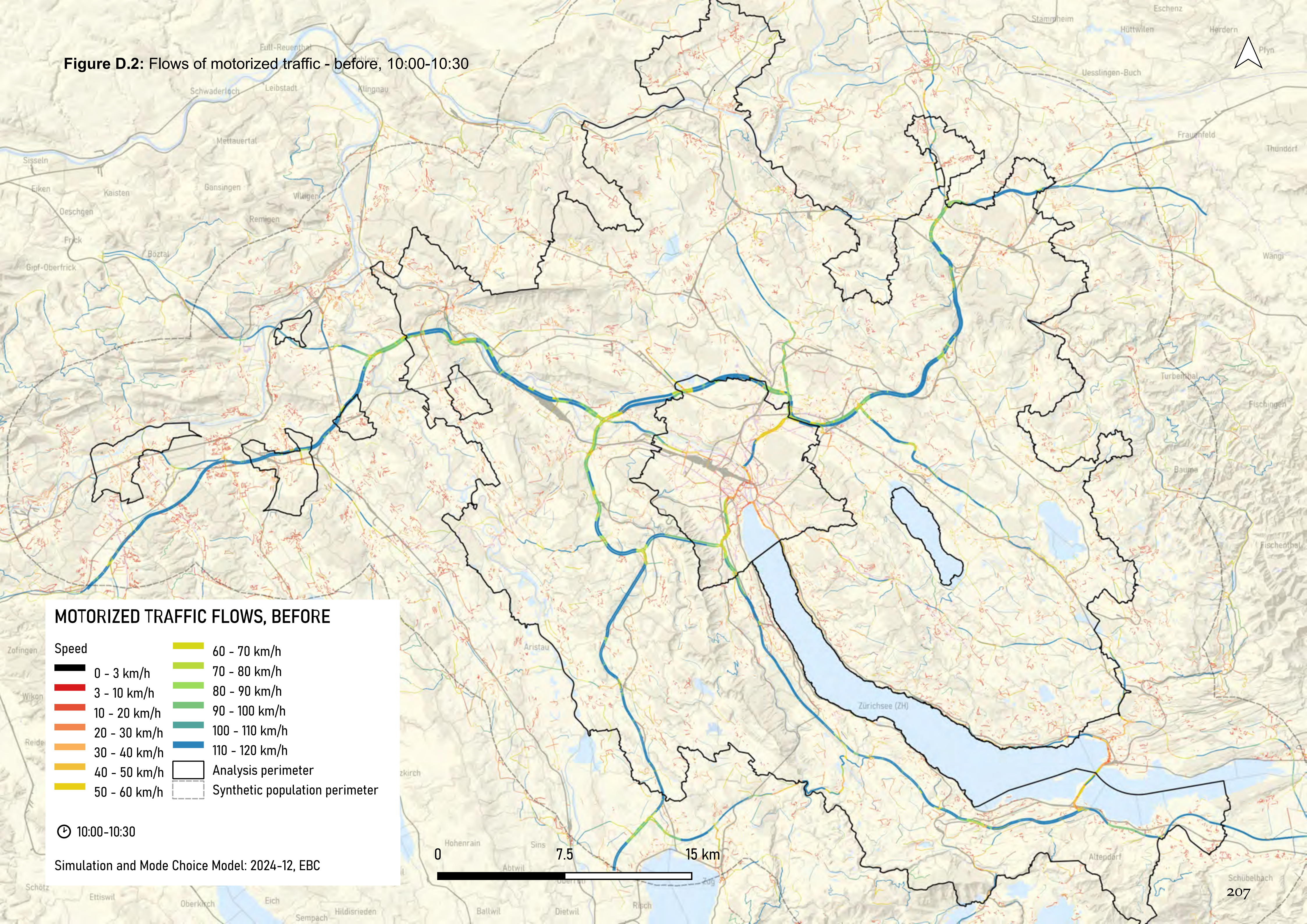


Figure D.3: Flows of motorized traffic - after, 10:00-10:30

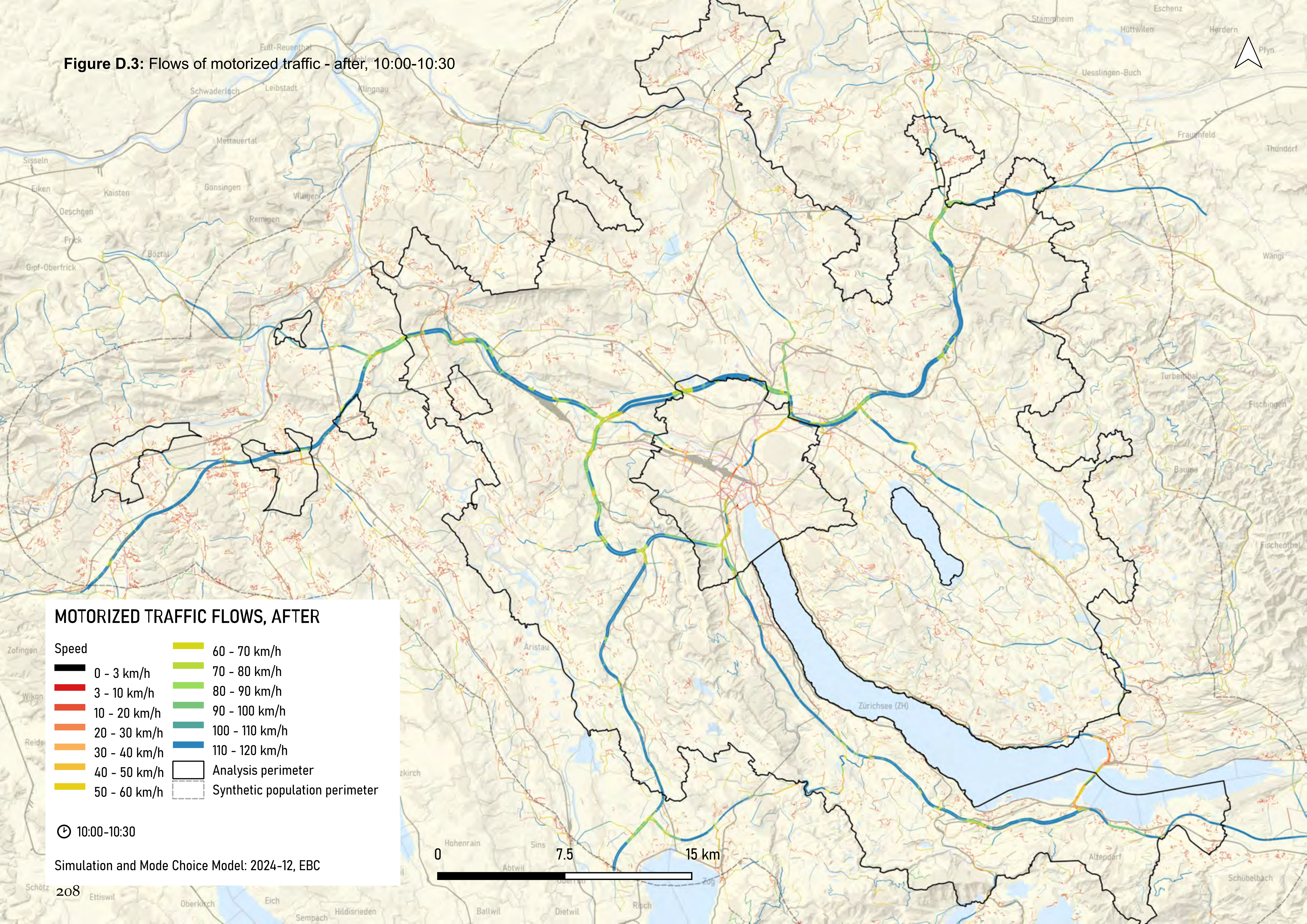


Figure D.4: Logsum accessibility changes on car trips, 10:00-10:30

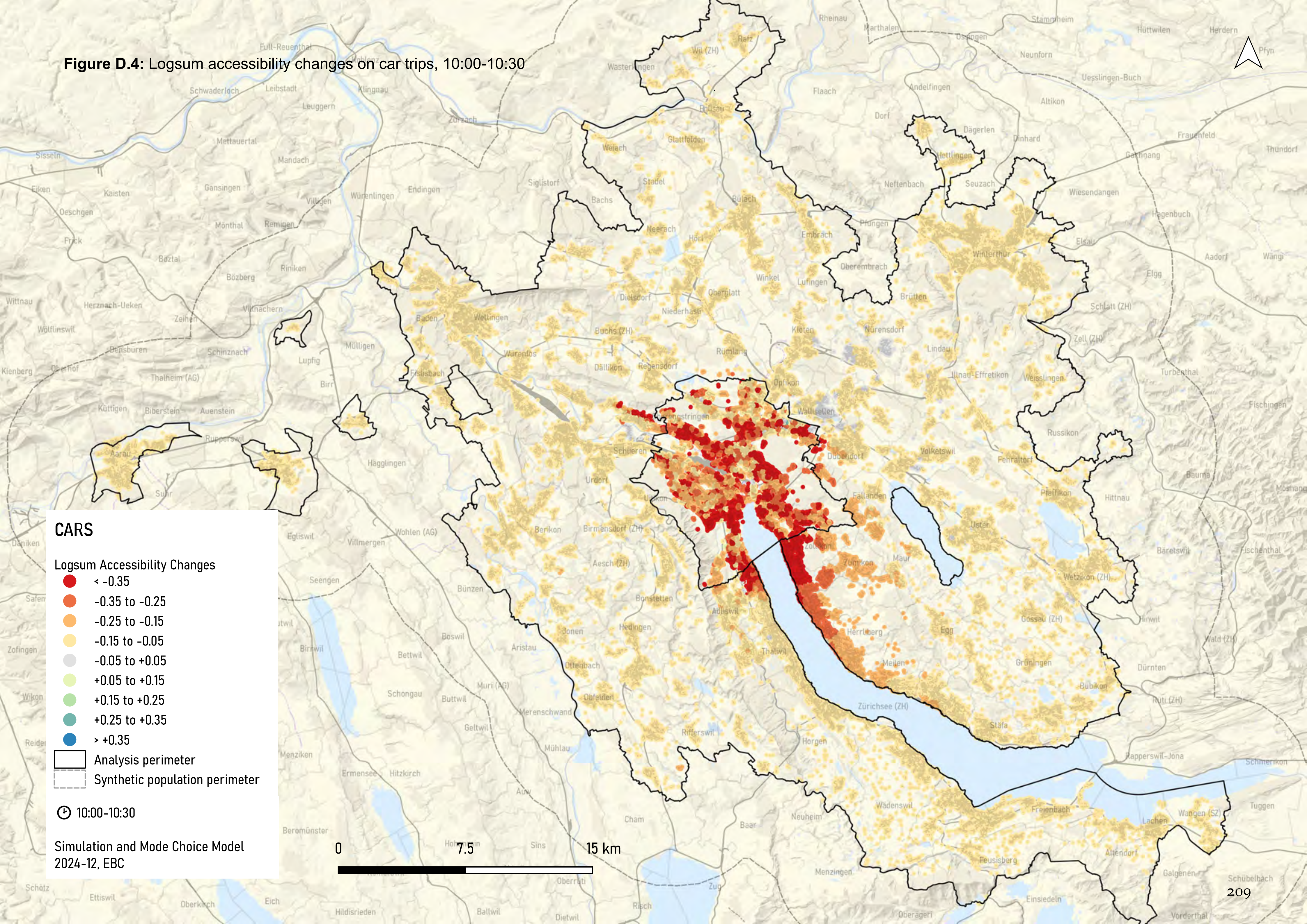
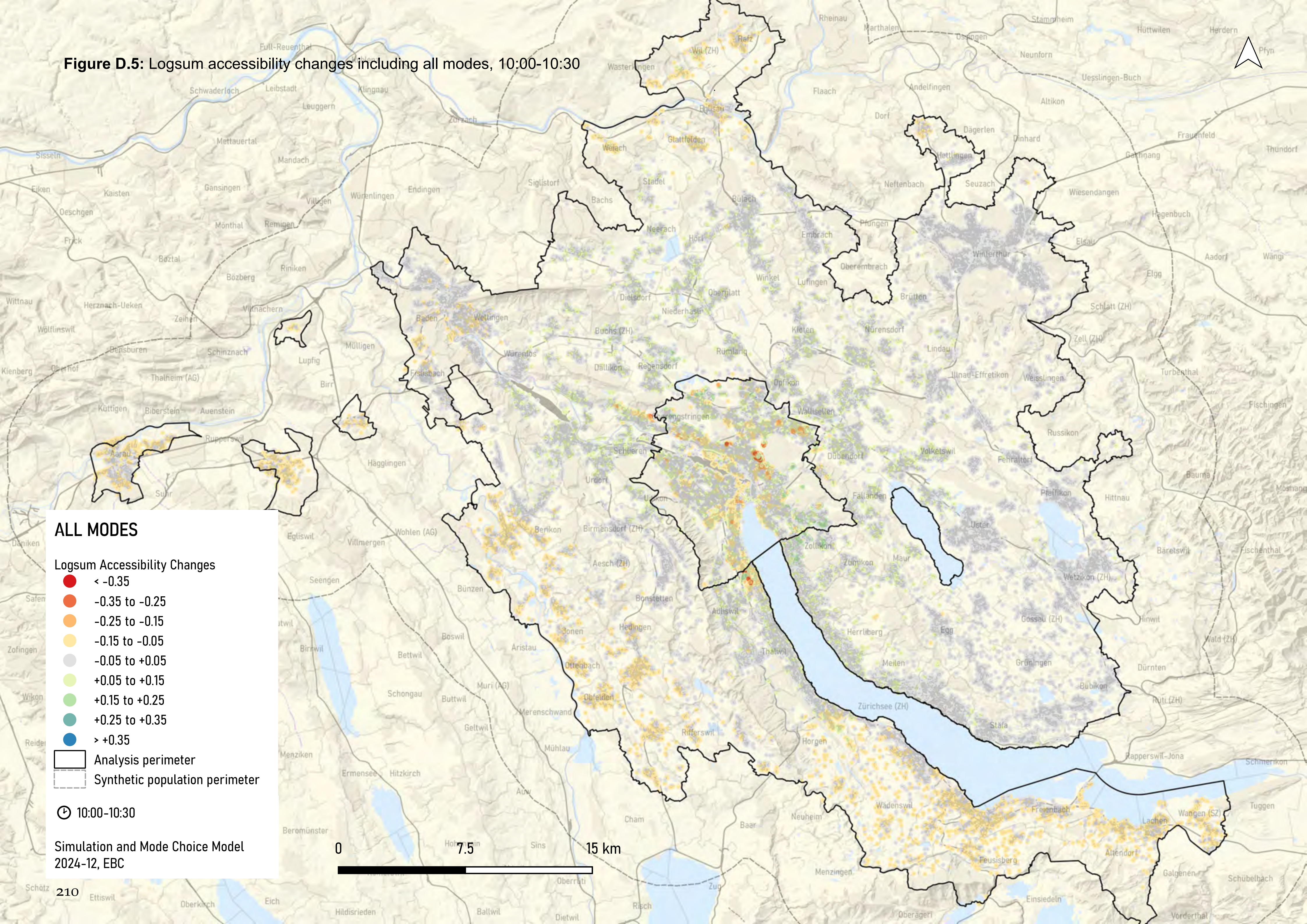


Figure D.5: Logsum accessibility changes including all modes, 10:00-10:30



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Curriculum Vitae

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Education

2021 – 2025	Eidgenössische Technische Hochschule Zürich, Zürich, Switzerland *Final degree:* Dr. sc. ETH Zurich
Sep 2023 – Feb 2024	Massachusetts Institute of Technology, Cambridge MA, USA *Academic exchange at the Department of Urban Studies and Planning*
2013 – 2016	Eidgenössische Technische Hochschule Zürich, Zürich, Switzerland *Final degree:* M.Sc. in Spatial Development and Infrastructure Systems *Distinctions:* Willi Studer Prize and ETH Silver Medal
2010 – 2013	Eidgenössische Technische Hochschule Zürich, Zürich, Switzerland *Final degree:* B.Sc. in Architecture

Employment

Oct 2021 – May 2025	Research Assistant *Institute for Transport Planning and Systems*, *Institute of Cartography and Geoinformation*, Zürich, Switzerland
Aug 2021 – Jun 2020	Head of Mobility Data Analytics *Bond Mobility (Europe) AG*, Zürich, Switzerland
Apr 2019 – Jun 2020	Co-Founder *Roll2Go AG*, Zürich, Switzerland
Dec 2016 – Mar 2019	Project Manager in Railway Infrastructure and Innovations *Schweizerische Südostbahn AG*, Samstagern, Switzerland
Mar 2015 – Jul 2015	Intern in Public Transport Network Development *Verkehrsbetriebe Zürich*, Zürich, Switzerland
Sep 2012 – Feb 2013	Intern in Architecture *Allemann Bauer Eigenmann Architekten*, Zürich, Switzerland

Publications

Articles in peer-reviewed journals

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Ballo, L. (2022) E-Bike City: Nachhaltig? Gerecht? Wünschenswert?, workshop at the *Universitätstagung Verkehrswesen*, Weimar, September 25-27.

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