Spatial Accessibility Modelling for Inclusive Mobility

Dissertation

zur

Erlangung der naturwissenschaftlichen Doktorwürde
(Dr. sc. nat.)

vorgelegt der
Mathematisch-naturwissenschaftlichen Fakultät
der
Universität Zürich

von
Alexandra Ioana Georgescu

aus
Rumänien

Promotionskommission

Prof. Dr. Robert Weibel (Vorsitz und Leitung)
Dr. Hoda Allahbakhshi (Leitung der Dissertation)
Prof. Dr. Alireza Darvishy
Prof. Dr. Ross Purves
Dr. Christina Röcke

Zürich, 2026

Abstract

Urban environments shape how individuals access facilities, the opportunities available to them, and their participation in social life. As cities expand and demographic changes lead to more diverse mobility needs, ensuring equitable access across urban areas has become increasingly important. Spatial accessibility, the ease with which individuals can reach desired destinations, is a key way to assess this. However, accessibility is not experienced equally across population groups. This is especially true for individuals with mobility restrictions, whose navigation of the built environment depends on microscale street elements (features within sidewalks, intersections, and other pedestrian areas, such as high kerbs, stairs, or tactile paving). These disparities relate to individual mobility capacities and to how such elements are perceived as barriers or facilitators.

However, existing approaches to assessing spatial accessibility often rely on simplified assumptions and coarse representations of pedestrian environments, omitting microscale street elements and the interaction between individual capacities and the built environment. Consequently, they provide only a limited and fragmented representation of how individuals navigate urban environments, as they rarely support systematic comparisons of how the same pedestrian environments affect people with different mobility capacities.

This thesis addresses these limitations by examining how internal factors (i.e., individual mobility capacities) and external factors (i.e., microscale street elements) shape spatial accessibility in pedestrian environments. To do so, the research is guided by four objectives: (1) to systematically identify microscale street elements influencing accessibility, (2) to assess how these elements are perceived by individuals with different mobility capacities, (3) to integrate such elements into pedestrian network representations, and (4) to model their combined impact on spatial accessibility patterns. The core contributions of the thesis are presented in four research papers (Chapters 2-5).

Chapter 2 establishes the foundation for the thesis by developing a comprehensive taxonomy of microscale street elements influencing urban pedestrian accessibility across population groups. Through a systematic literature review, it identifies relevant microscale street elements, analyses research trends including the population groups studied and the methodologies used, and classifies their perceived barrier and facilitating effects. The resulting taxonomy highlights how the influence of microscale street elements varies across population groups, while revealing key gaps in current accessibility research.

Chapter 3 quantifies how individuals with different mobility capacities perceive the severity and facilitating effects associated with microscale street elements. Using an online survey, it enables systematic comparisons of how different population groups perceive microscale street elements and provides empirical evidence of between-group differences. The findings demonstrate that microscale street elements are not experienced uniformly across populations, with

substantial variation in perceived impacts both between and within groups, highlighting the importance of accounting for individual heterogeneity when assessing pedestrian accessibility.

Chapter 4 introduces a generalisable workflow for constructing enriched pedestrian networks with fine-grained accessibility information. By integrating microscale street elements into pedestrian network representations, the workflow enables their incorporation into accessibility models and supports the simulation of how environmental features influence individuals' movement. This allows accessibility constraints to be represented across space and between individuals while explicitly linking accessibility outcomes to specific street elements, and enabling the assessment of their individual and cumulative effects.

Chapter 5 demonstrates how differences in mobility capacities translate into accessibility disparities through a fine-grained accessibility modelling framework, calibrated using empirical perception data. By integrating microscale street elements with individuals' perceptions of their barrier and facilitating effects, the framework enables the evaluation of accessibility across multiple spatial scales, from individual routes to district-wide patterns. The results show that differences in perception translate into substantial variation in accessibility outcomes, with localised environmental constraints accumulating to create broader accessibility inequalities, including areas of limited or no accessibility ('islands of inaccessibility') within the pedestrian network.

Overall, this thesis advances the conceptual understanding of accessibility as an emergent property of the interaction between environmental characteristics and individual mobility capacities, rather than an inherent feature of the built environment. It provides empirical evidence on how microscale street elements are perceived across population groups and introduces a transferable methodological framework integrating environmental data and perception-based measures into computational accessibility modelling. Furthermore, this framework supports urban planning by enabling the identification of accessibility barriers, the simulation-based evaluation of design interventions, and the prioritisation of improvements across population groups. The findings underline the importance of addressing physical barriers as a prerequisite for inclusive mobility and show that accessibility inequalities are largely driven by microscale street elements, requiring policies that account for both between- and within-group heterogeneity.

Acknowledgements

This dissertation was carried out as part of the SISAL project and was funded by the Digitalization Initiative of the Zurich Higher Education Institutions (DIZH). It further benefited from the interdisciplinary and inter-institutional collaboration between the University of Zurich, the Digital Society Initiative, the Department of Geography, the Healthy Longevity Center, and the Zurich University of Applied Sciences.

Throughout my PhD journey, I have been incredibly fortunate to be surrounded by many wonderful people whose support is difficult to fully express in words. Nevertheless, I would like to take this opportunity to thank, in particular:

Hoda Allahbakshi, for your tremendous and constant support throughout this journey. For your patience as I found my footing, for trusting me with this project, and for your invaluable guidance along the way. You have opened so many doors for me, exposing me to new ideas, opportunities, and experiences I would not have had otherwise. I have learned so much from you over these past four years, and I thank you for all the valuable advice you have shared with me, for empowering me to be independent and to find my own research identity, and for all the kind encouragement you have given me every step of this journey. I greatly admire your passion and commitment to research, and I know that this thesis would not have been possible without you.

Robert Weibel, for your incredible mentorship over the years, for your guidance and support, and for your genuine interest and constant encouragement when it was needed most. Your knowledge and passion for research, and your dedication to your students, never cease to amaze me, and I have always found that deeply inspiring. Thank you for giving me this opportunity, and in many ways, for inspiring me to pursue a PhD in the first place during our time working together on my MSc thesis. After more than five years of working together, including my MSc project, I take away so much more than just research experience, and that is thanks to you. I am certain this journey would not have been as rewarding without your support.

Alireza Darvishy, for your support in the efficient recruitment of participants for the data collection, and for your valuable insights on conducting it in an inclusive manner.

Ross Purves, for your thoughtful input at every committee meeting, your support with data collection, and for fostering such a welcoming and engaging environment, both formally as Head of the Graduate School and now as Head of Department.

Christina Röcke, for your constant support, constructive feedback, and invaluable assistance with the survey data collection, including connecting me with the right people and helping ensure its successful completion. I truly admire your energy and passion for your work.

Sandra Oppikofer, for your kind and prompt support in bringing the data collection to completion at a particularly stressful stage of the process.

Sabine Timpf, for kindly agreeing to serve as the external examiner for my dissertation and for your valuable time and effort.

Collaborators from various departments within the City of Zurich, particularly François Rüttimann, Birger Schmidt, Wernher Brucks, Myriam Fojtu, and Flavia Frei, for your continuous support, your interest in my project, and for taking the time to engage with my research and share valuable practice-based insights that helped ground it.

The ZüriACT and ZuReach project teams, especially Alireza, Annina, Cassandra and Chiara, for your support and contributions to my project, and for facilitating and easing the extensive data collection process. I would also like to thank the participants of the ZüriACT project and those who took part in my study for their time and contributions, without which this research would not have been possible.

Friends and colleagues from the DSI, especially Nina Cornelius, for your support, your friendship and for making the DSI Excellence Program so fun and enriching. To all the PhD students in my cohort, for making this journey much more enjoyable. I especially want to thank Federica for your kind support, excellent organisational skills, and for being such an inspiration, as I see you going after everything you want and achieving it. Thank you, Ibra, for your contagious positive energy, always reminding me that nothing is the end of the world and putting a smile on my face, and for the many dinners, confetti and concerts attended together. Finally, thank you, Donatella, for your sincere friendship, for our endless discussions and pick-me-up coffees, for always giving me a shoulder to cry on and showing me that I am not alone in this journey.

Friends and colleagues from GIUZ: Alex, Armand, Changyu, Cheng, Corrado, Daniela, Eleni, Inhye, Joris, Kaan, Karin, Katia, Lara, Leonie, Mina, Nico, Peter, Qi, Sergio, Simon, Takuya, Tiziana, Tumasch, Zhiyong, and many others, for the endless coffees and lunches shared together, endless laughs, engaging conversations and for creating a wonderful environment around. I will miss all this dearly.

To friends here in Switzerland, especially Alice, Anna, Elena, Fabian, Hendrik, Joseph, Julie, Letizia, Noelia, Paolo, Sigma, Simon, Sofia, and Weronika, for making both Zurich and Bern feel so welcoming and truly like a second home. Special thanks also to my long-distance friends, especially Andreea, Dani, Flavia, Ioana, Miguel, Nico and Raluca, who, despite the distance, made countless efforts to visit, supported me through all the ups and downs of this journey, and made the distance feel insignificant in the face of the bond we share.

To my Mom and Dad, without whom I would not be here. Thank you for always encouraging me and for giving me the opportunity to study abroad not once, but twice. Thank you for everything you have given me and for making it possible to follow my dreams. To my sister, Dora, thank you for all your support, all the video calls that made me feel closer to home, and for everything you did that meant more than you know. Finally, to Ioana, for being my rock, for your constant encouragement, and for helping me through the low points and making the high points even more special. Thank you for your patience, for always

motivating me, and for being my number one supporter, no matter what. I do not know how I would have done this without you. And to my cat Pixel, for the emotional support, naps on my keyboard, and for making sure I always take a break for our daily walk outside.

Contents

Abstract i

Acknowledgments iii

1 Introduction 1
- 1.1 Motivation . . . 1
- 1.2 Positioning the research . . . 3
  - 1.2.1 Spatial accessibility . . . 3
  - 1.2.2 Contextual factors: individuals' mobility capacities and microscale street elements . . . 6
- 1.3 Research gaps and research objectives . . . 9
  - 1.3.1 RO1: Identify microscale street elements influencing spatial accessibility 10
  - 1.3.2 RO2: Assess perceived impacts of microscale street elements . . . 10
  - 1.3.3 RO3: Enrich pedestrian networks with microscale street elements . . . 11
  - 1.3.4 RO4: Model the impact of microscale street elements and individuals' subjective perceptions on accessibility patterns . . . 12
- 1.4 Population groups considered and study area . . . 12
  - 1.4.1 Population groups . . . 12
  - 1.4.2 Study area . . . 13
- 1.5 Thesis structure and overview . . . 13
  - 1.5.1 Structure of the thesis . . . 13
  - 1.5.2 Overview of thesis chapters . . . 13
  - 1.5.3 Related publications . . . 16

2 Microscale street elements influencing spatial accessibility 17
- 2.1 Introduction . . . 19
- 2.2 Methodology . . . 21
  - 2.2.1 Research questions . . . 21
  - 2.2.2 Literature search . . . 22
  - 2.2.3 Eligibility criteria . . . 22
  - 2.2.4 Article selection . . . 22
  - 2.2.5 Data extraction . . . 23
- 2.3 Results . . . 24
  - 2.3.1 Participants and their characteristics . . . 24
  - 2.3.2 Data collection methods . . . 26
  - 2.3.3 Street elements . . . 27
    - 2.3.3.1 Barriers . . . 28

2.3.3.2 Facilitators . . . 29
2.3.4 Street element frequency . . . 29
2.4 Discussion . . . 32
2.4.1 Participants and their characteristics . . . 32
2.4.2 Data collection methods . . . 34
2.4.3 Street elements and their frequency . . . 35
2.4.4 Limitations . . . 37
2.5 Conclusion . . . 38

3 How mobility restrictions shape perceptions of pedestrian infrastructure 41
3.1 Introduction . . . 43
3.2 Related work . . . 44
3.3 Materials and methods . . . 46
3.3.1 Participant recruitment and questionnaire administration . . . 46
3.3.2 Questionnaire design and development . . . 47
3.3.3 Statistical analysis . . . 47
3.3.3.1 Between-groups variation . . . 47
3.3.3.2 Within-groups variation . . . 48
3.3.4 Perceptual influences on movement and accessibility . . . 48
3.4 Results . . . 49
3.4.1 Sample description . . . 49
3.4.2 Between-groups variation . . . 49
3.4.2.1 Impact of barriers . . . 49
3.4.2.2 Impact of facilitators . . . 52
3.4.3 Within-groups variation . . . 54
3.4.3.1 Mobility assistive device . . . 54
3.4.3.2 Gender . . . 54
3.4.3.3 Age . . . 55
3.4.4 Perceptual influences on movement and accessibility . . . 55
3.5 Discussion . . . 57
3.5.1 Between-groups heterogeneities . . . 57
3.5.2 Within-groups heterogeneities . . . 59
3.5.3 Perceptual influences on movement and accessibility . . . 60
3.5.4 Limitations . . . 61
3.6 Conclusions . . . 62

4 Developing enriched pedestrian networks with accessibility information 63
4.1 Introduction . . . 65
4.2 Data . . . 66
4.3 Methods . . . 66
4.3.1 Preprocessing of pedestrian network . . . 66
4.3.2 Preprocessing of accessibility features . . . 67
4.3.3 Impedance score calculation . . . 68
4.3.4 Data and software availability . . . 68
4.4 Results . . . 68
4.5 Discussion . . . 70

5 Impact of microscale street elements on accessibility disparities 73
5.1 Introduction . . . 75
5.2 Background . . . 76
5.2.1 Terminology . . . 76
5.2.2 Related work . . . 77
5.3 Materials and methods . . . 78
5.3.1 Study area . . . 78
5.3.2 Data . . . 79
5.3.3 Survey design and participants . . . 80
5.3.4 Methodology . . . 81
5.3.4.1 Pedestrian network enrichment . . . 81
5.3.4.2 Impedance score calculation . . . 82
5.3.4.3 Accessibility patterns analysis . . . 85
5.3.4.4 Between-groups comparison . . . 86
5.4 Results . . . 87
5.4.1 Impedance score . . . 87
5.4.2 Accessibility patterns . . . 88
5.4.3 Between-groups comparison . . . 89
5.5 Discussion . . . 93
5.5.1 Pedestrian network enrichment . . . 93
5.5.2 Impedance score . . . 95
5.5.3 Accessibility patterns . . . 95
5.5.4 Between-groups comparison . . . 96
5.5.5 Limitations . . . 97
5.6 Conclusion . . . 98

6 Synthesis 100
6.1 Main findings by research objective . . . 100
6.1.1 Identify microscale street elements influencing spatial accessibility (RO1) 100
6.1.2 Assess perceived impacts of microscale street elements (RO2) . . . 102
6.1.3 Enrich pedestrian networks with microscale street elements (RO3) . . . 105
6.1.4 Model the impact of microscale street elements and individuals' subjective perceptions on accessibility patterns (RO4) . . . 106
6.2 Key insights . . . 108
6.3 Implications for practice . . . 109
6.4 Limitations . . . 111
6.5 Outlook . . . 113

References 117

A Supplementary Material for Chapter 2: Microscale street elements influencing spatial accessibility 129
A.1 Complete list of elements perceived as barriers or facilitators in included studies 129

B Supplementary Material for Chapter 3: How mobility restrictions shape perceptions of pedestrian infrastructure 132
B.1 Questionnaire . . . 132

B.2 Microscale street elements 142
B.3 Survey participants 143
B.4 Between-groups variation 145
B.5 Within-groups variation 148

C Supplementary Material for Chapter 4: Developing enriched pedestrian networks with accessibility information 153
C.1 Description of accessibility features and tags 153
C.2 Description of accessibility features reclassification 154

D Supplementary Material for Chapter 5: Impact of microscale street elements on accessibility disparities 155
D.1 Distribution of accessibility features 155

1 Introduction

1.1 Motivation

Urban environments are dynamic systems shaped by the interactions between humans, the built environment, and the spatial distribution of social and economic activities (Batty, 2008). In this context, access to desired destinations is a fundamental dimension of urban life, influencing the ability to reach jobs, supermarkets, healthcare, and other essential services, as well as to participate in social life (Hansen, 1959). This capacity, termed *spatial accessibility* in this thesis (Section 1.2.1), plays a crucial role in determining how easily individuals can access opportunities and services that structure their daily routines. However, these opportunities are not evenly distributed across population groups. For example, individuals with disabilities may face challenges navigating the built environment or using transport systems that are not designed to accommodate diverse needs (Lid & Solvang, 2016).

The primary role of a transport network is to facilitate connections among people, places, and activities throughout urban space (Miller, 2018). Its infrastructure determines how easily individuals can move within it, reach destinations, and engage in everyday activities. These connections are enabled through various travel modes, including private vehicles, public transport, cycling, and walking. Among these, *walking* is the most fundamental and universally accessible form of mobility, involved in the majority of trips either as the primary mode or as a link to other modes such as public transport or private vehicles (D'Orso & Migliore, 2020).

Consequently, pedestrian accessibility is fundamental for enabling individuals to navigate urban environments. Sidewalks, intersections, and pedestrian areas constitute key elements of the infrastructure that support safe and continuous pedestrian movement (Corazza et al., 2016). Further, ensuring accessible pedestrian infrastructure is becoming more important as urban populations continue to grow and the need for inclusive urban environments becomes increasingly recognised. Over the past decades, cities have experienced significant population growth, with projections estimating that nearly two-thirds of the world's population will reside in urban areas by 2050 (United Nations, 2019). As a result, a growing share of the population will depend on the pedestrian infrastructure.

Despite its central role in connecting people to opportunities, the pedestrian network is not experienced equally across individuals. In practice, the ability to reach destinations is often lower for people with mobility restrictions than for those without (Achuthan et al., 2010; Orellana et al., 2020; Vale et al., 2017). These disparities can be reflected in longer and more complex routes, a reduced set of reachable destinations or increased travel effort.

Activities that may be relatively straightforward for individuals without mobility limitations, such as climbing stairs, navigating crowded streets, or completing everyday errands on a rainy day, can present significant challenges for those with mobility restrictions (Gharebaghi et al., 2021). A distance considered easily walkable for many people may require substantial effort for individuals with mobility impairments or older adults with reduced walking speed. Wheelchair users may be unable to navigate narrow sidewalks (Kasemsuppakorn & Karimi, 2009), visually impaired pedestrians may encounter difficulties when obstacles such as newspaper stands, advertising boards, or outdoor seating obstruct pedestrian paths (Lid & Solvang, 2016), and older adults may experience fatigue more quickly when adequate seating or resting opportunities are unavailable (Koon et al., 2020).

Environmental barriers can have significant consequences for individuals with mobility restrictions, affecting not only their ability to participate in daily activities but also their overall well-being. These constraints have been closely associated with negative physical and mental health outcomes (Gamache et al., 2019; Portegijs et al., 2020). When environments are difficult or unsafe to navigate, individuals may reduce their participation in outdoor activities and social interactions, limiting engagement in everyday activities such as physical exercise. In some cases, individuals with visual impairments or other mobility restrictions may avoid certain urban areas altogether when environmental conditions make navigation too difficult or unpredictable (Lid & Solvang, 2016). Such barriers can undermine individuals' sense of autonomy and independence and contribute to feelings of loneliness when participation in outdoor life becomes restricted (Rantakokko et al., 2014). In some cases, persistent barriers may confine individuals to limited areas of the city or even to their homes, increasing the risk of social isolation (Macdonald et al., 2018).

Broader demographic and societal trends further highlight the importance of inclusive and well-functioning urban environments. The global population is ageing, with the share of people aged 65 and over projected to increase from 9% in 2019 to 16% by 2050 (United Nations, 2021). In addition, approximately 16% of the world's population lives with some form of disability (World Health Organization, 2022). These trends imply that a growing share of the population will experience mobility limitations or specific mobility-related needs within urban environments. Thus, improving the ability to reach destinations and move within cities has become increasingly important for supporting inclusive mobility and ensuring equitable participation in urban life.

In this context, accessibility analysis provides an important analytical framework for understanding how urban environments enable or constrain individual mobility. Spatial accessibility models enable examination of how the spatial distribution of infrastructure, services, and transport networks influences the opportunities available to different population groups. Furthermore, such models can capture the diverse challenges faced by individuals with different needs, including those with mobility restrictions or disabilities. In doing so, accessibility analysis helps reveal how the built environment and pedestrian networks shape movement patterns and can highlight spatial disparities in access to opportunities across populations and urban areas.

1.2 Positioning the research

The preceding section highlighted the importance of spatial accessibility in urban environments and emphasised that access to opportunities is not experienced equally across populations. Building on this motivation, this section situates this research within the broader academic literature and reviews key approaches to conceptualising and measuring accessibility.

1.2.1 Spatial accessibility

Accessibility has long been recognised as a complex and "slippery" concept (Gould, 1969) that has been defined in several ways within transport geography and urban planning. Some definitions emphasise the availability of opportunities for interaction (Hansen, 1959), others focus on the extent to which transport systems enable individuals to reach desired destinations (Geurs & Van Eck, 2001), while still other perspectives highlight the relationship between individuals' mobility capabilities and the spatial distribution of services and opportunities (Litman, 2003). Together, these perspectives frame accessibility as a multidimensional concept that links transport systems, land-use patterns, and individual mobility capacities. Recognising this multidimensionality is essential for understanding how accessibility may vary across individuals and urban contexts, and for analysing how characteristics of the built environment and mobility constraints shape access to opportunities.

Building on this multidimensional understanding, spatial accessibility is commonly conceptualised as the outcome of several interrelated components that shape how opportunities are reached. A widely used framework proposed by Geurs and Van Wee (2004) distinguishes four key components: transport, land use, time, and individual characteristics. These components capture the spatial distribution of opportunities, the costs and conditions of travel, temporal constraints, and individuals' abilities and resources. The individual component mediates the other dimensions, as the *ease of reaching opportunities* varies across individuals and is influenced by their needs, capabilities and perceptions of the built environment around them (De Vos et al., 2025). This mediating role has been further emphasised in research on activity spaces and daily mobility, which shows that individuals selectively engage with only a subset of spatial opportunities depending on routines, constraints, and preferences (Cagney et al., 2020; Hirsch et al., 2016; Jones & Pebley, 2014; Schönfelder & Axhausen, 2003).

Given the diversity of perspectives in the literature, it is necessary to clarify how spatial accessibility is understood in the context of this thesis. Building on Allahbakhshi (2023), spatial accessibility is defined as follows:

> **Spatial accessibility**, also referred to as **accessibility** in this thesis, is understood as the ease with which destinations such as services or places of social interaction can be reached from a given location through movement in physical space.

In addition to accessibility, the concept of *walkability* is frequently used in the literature to describe how supportive an environment is for walking (Forsyth, 2015). While accessibility focuses on the potential to reach destinations, walkability refers more specifically to the extent to which the built environment facilitates walking as a mode of transport. It is commonly associated with characteristics such as sidewalk quality, connectivity, safety, land-use mix,

aesthetics, and the presence of pedestrian-friendly infrastructure (Lo, 2009), and has been measured using a range of composite indicators that capture both structural and experiential characteristics of the built environment (Ewing & Handy, 2009). One of the most well-known such indicators, widely used globally to quantify the walkability of a location, is Walk Score (Hall & Ram, 2018), which calculates walkability based on the distance of a location to different types of amenities and facilities.

In this context, walkability studies have been broadly classified into two categories based on how walkability is defined and measured: those that conceptualise walkability as a function of urban design and micro-level physical features of the built environment, such as enclosure, sidewalk width, the presence of shops, lighting conditions, building facades (e.g., doors and windows), street furniture, and pedestrian infrastructure elements such as kerbs and crossings; and those that emphasise macro-level characteristics of urban form, including residential density, land-use mix, street network connectivity, and the spatial distribution and proximity of facilities across neighbourhoods (Ewing & Handy, 2009; Shields et al., 2023).

Walkability is particularly important for individuals with disabilities, as it directly influences their ability to participate in out-of-home activities and maintain an active lifestyle (Schreuer et al., 2019). Empirical evidence shows that built environment characteristics such as land-use mix, street connectivity, and slope, as well as perceived environmental barriers, can significantly affect participation levels, especially for individuals with physical mobility impairments (Schreuer et al., 2019). Although closely related, walkability and accessibility capture different aspects of urban mobility. Walkability can be understood as a determinant of pedestrian accessibility, as more walkable environments generally enable easier movement through the built environment. However, high walkability does not necessarily imply high accessibility, as accessibility also depends on the distribution of destinations and individuals' ability to reach them.

Spatial accessibility can be measured using a variety of approaches, each capturing different aspects of how individuals reach opportunities across space. Geurs and Van Wee (2004) distinguish four main perspectives: location-based measures that examine the spatial distribution of opportunities, person-based measures that consider individuals' space–time constraints, infrastructure-based measures that focus on the characteristics of transport networks, and utility-based measures that evaluate the benefits individuals derive from accessing opportunities. Person-based approaches are closely related to time-geographical perspectives, which emphasise that individuals' access to opportunities is structured by space–time constraints arising from daily schedules, obligations, and temporal limitations (Hägerstrand, 1970). While each perspective highlights an important dimension of accessibility, none alone fully captures the complexity of the concept. Combining insights from these approaches can therefore help provide a more comprehensive understanding of accessibility and the factors that shape access to opportunities.

In addition to calculated measures such as those described above, spatial accessibility can also be understood from a subjective perspective, reflecting how individuals perceive their ability to access opportunities. Accessibility measures typically rely on spatial data and transport network characteristics to estimate the ease of reaching destinations (Marwal & Silva, 2022), but the resulting metrics do not fully capture how accessibility is experienced in everyday life.

Perceived accessibility refers to individuals' evaluations of their ability to access opportunities and participate in daily activities (Lättman et al., 2016; Pot et al., 2021). These perceptions can arise from how individuals interpret land use, transport, and temporal conditions, drawing on their own capabilities and experiences (Lättman et al., 2016; Lotfi & Koohsari, 2009). As a result, perceived accessibility may differ from calculated accessibility, helping explain why travel behaviour and activity participation do not always correspond to objective accessibility indicators. Spatial accessibility, therefore, varies substantially across individuals. People with physical or cognitive impairments, for example, may experience significantly different levels of accessibility than those without such constraints (Jehle et al., 2024; Vale et al., 2017). Recognising these differences is essential for understanding accessibility inequalities and for designing transport systems that support inclusive participation in everyday life.

This perceived spatial accessibility can also be understood in relation to mobility. While accessibility refers to the potential to reach opportunities, mobility reflects the realised movements through which these opportunities are accessed. However, the translation of accessibility into mobility is not automatic and depends on a range of individual and contextual factors. In this regard, mobility can be further differentiated into *motility*, defined as the set of factors that shape an individual's capacity to move (Kaufmann, 2002), and *movement*, which refers to the actual manifestation of mobility in space (Shareck et al., 2014). Motility emphasises that individuals differ in their ability to make use of available opportunities, as it is shaped by interrelated elements of access, competence, and appropriation (Kaufmann et al., 2004). Here, access refers to the set of opportunities available within the spatial system, competence encompasses the physical abilities and skills required to make use of these opportunities, and appropriation captures how individuals evaluate, select, and act upon mobility options. These elements highlight that spatial accessibility is not solely determined by external conditions but is filtered through individual capacities, resources, and decision-making processes. As a result, spatial accessibility is inherently context-dependent and centred on the individual, with similar spatial conditions potentially leading to very different mobility outcomes depending on how these various factors interact in everyday life.

Conclusion. Spatial accessibility is thus understood as a context-dependent concept that extends beyond the spatial distribution of opportunities. While conventional measures capture the potential to reach destinations, accessibility ultimately depends on how these opportunities are perceived and translated into mobility in everyday life. This translation is not straightforward but is shaped by contextual factors such as individuals' mobility capacities, resources, and perceptions, as well as by environmental conditions, including microscale street elements, such as sidewalk quality, high kerbs or stairs, that influence how opportunities can be reached. As a result, access to opportunities is not uniform, but can vary across individuals according to their circumstances and constraints, and may therefore not be fully reflected by objective indicators alone. Considering both the measurable and perceptual dimensions of spatial accessibility enables a more comprehensive understanding of how opportunities are accessed in practice.

1.2.2 Contextual factors: individuals' mobility capacities and microscale street elements

Spatial accessibility is often assessed using indicators such as travel distance, travel time, or network connectivity (Neutens, 2015). While these indicators capture aspects of network structure and travel costs, they may overlook how features of the pedestrian environment influence individuals' ability to move through the urban environment. Considering the interaction between mobility capacities and characteristics of the built environment is therefore essential for understanding accessibility in pedestrian settings and for informing more inclusive urban planning strategies.

Numerous contextual factors can influence an individual's spatial accessibility, including *external factors*, that is, conditions of the surrounding environment such as characteristics of the built environment, weather conditions, or socio-economic context, and *internal factors*, which relate to the individual's own abilities and resources, such as personal mobility capacities (Terefe & Hou, 2024). Among these, however, the built environment and individual mobility capacities play a particularly fundamental role because they directly determine whether movement between locations is physically possible (Neven & Ectors, 2023). Thus, this thesis focuses on the interaction between characteristics of the built environment and individuals' mobility capacities as key determinants of spatial accessibility.

> The **mobility capacities** of an individual refer to the physical abilities, resources, and conditions that enable a person to move independently through space from one location to another and access facilities, services, and opportunities.

Internal factors such as an individual's mobility capacities are widely recognised in the literature as key contextual determinants of spatial accessibility (Kapsalis et al., 2024). The mobility capacities of an individual may vary due to factors such as impairment, health conditions, ageing or situational circumstances (e.g., carrying heavy luggage or pushing a stroller), and can dictate the ability of individuals to walk certain distances (e.g., 1–2 km), the ability to stand for long periods of time, the ability to climb stairs, and the sensory and orientation abilities required to navigate environments safely and efficiently. Thus, mobility capacities can directly shape how individuals navigate urban environments (Lid & Solvang, 2016), by influencing how far and fast people can travel. Furthermore, how individuals navigate urban environments can also be shaped by internal factors beyond physical mobility capacities, such as safety perceptions, confidence, and prior experience (Gharebaghi et al., 2021; Ståhl et al., 2008). As a result, environments perceived to involve greater risks, such as falling, collisions with traffic, or unexpected obstacles, may increase the perceived difficulty of navigating urban space, meaning that accessibility is shaped not only by objective environmental characteristics but also by individuals' perceived safety, effort, and risk. However, this thesis focuses on individuals' *physical mobility capacities* and how these influence spatial accessibility.

One of the main reasons accessibility disparities arise between individuals with and without mobility restrictions or impairments is the mismatch between individuals' mobility capacities and the requirements of the built environment (Cepolina & Tyler, 2004; Tyler, 2006). When environmental demands, such as distance, slopes, steps, or sidewalk surface conditions, exceed

an individual's mobility capacities, the ability to move through and access urban spaces becomes constrained. Individuals may partially compensate for these limitations by using assistive devices, such as wheelchairs, walkers, rollators, walking sticks, or white canes, which can support independent mobility. Consequently, accessibility is strongly shaped by how individuals' mobility capacities interact with the microscale street elements of the pedestrian environment. Spatial accessibility in pedestrian environments can therefore be understood as the outcome of the interaction between individuals' mobility capacities and the environmental demands imposed by microscale street elements.

> **Microscale street elements**, also referred to as **accessibility features** throughout this thesis, are physical features of the pedestrian environment found along sidewalks, intersections or pedestrian areas. These include street furniture or streetscape elements (e.g., poles, trees, planters, benches, street lights); sidewalk surface characteristics such as material (e.g, cobblestones or asphalt) and condition (e.g., smooth, uneven or cracked); as well as intersection elements (e.g., kerb ramps, condition of zebra crossing or accessible pedestrian signals).

Spatial accessibility in pedestrian environments is largely shaped at the sidewalk level, where microscale street elements play a crucial role in how people move through the urban environment (Harris et al., 2015; Jenkins et al., 2015; Park & Chowdhury, 2018; Šakaja et al., 2019; Wazani et al., 2021). For walking trips in particular, microscale street elements can play an equally important, or even more important, role in shaping accessibility than factors such as network connectivity or the spatial distribution of facilities (Bivina et al., 2020). For example, individuals with different mobility restrictions or impairments often choose accessible, barrier-free routes, even when this requires longer travel distances to their destination (Gharebaghi et al., 2021).

Microscale street elements can act as either barriers or facilitators:

- **Barriers.** These include features such as stairs, uneven surfaces such as cobblestones, or temporary obstructions such as construction sites. They can hinder or prevent movement, forcing individuals to change routes, take lengthy detours, or even stop altogether, thereby reducing the set of destinations that can be realistically reached.
- **Facilitators.** In contrast, features such as pedestrian signals, kerb ramps, tactile paving, or available seating can enable and support movement. They can reduce physical effort, improve safety and orientation, and help compensate for restricted or declining mobility capacities, thereby expanding the range of destinations that can be reached.

Furthermore, microscale street elements can affect accessibility differently depending on individuals' mobility capacities (Jehle et al., 2024). For example, a wheelchair user may encounter different barriers to everyday mobility than an older adult or a visually impaired individual. Consequently, certain elements of the pedestrian environment may function as barriers for some groups while acting as facilitators for others. Street furniture, for instance, may support navigation and orientation for visually impaired pedestrians (Rey-Galindo et al., 2020), yet it can also reduce the effective width of sidewalks, thereby creating obstacles for wheelchair users (Harris et al., 2015) or individuals pushing strollers. Similarly, high kerbs

may represent a barrier for wheelchair users by preventing them from crossing the street (Aldersey et al., 2018; Harris et al., 2015; Rosenberg et al., 2013; Šakaja et al., 2019; Wazani et al., 2021), while at the same time serving as a useful tactile boundary that helps visually impaired individuals distinguish the sidewalk from the roadway (Han et al., 2020).

Moreover, the effects of microscale street elements differ not only between impairment groups but also within the same group due to variations in mobility capacities. For example, older adults represent a highly heterogeneous group, ranging from individuals who remain highly mobile to those who rely on mobility aids such as rollators or mobility scooters (Rosenberg et al., 2013). As a result, members of the same group may experience the pedestrian environment differently and face varying levels of accessibility. Taken together, these considerations highlight the importance of understanding not only which microscale street elements influence accessibility for individuals with different mobility capacities, but also how this impact differs *between* and *within* different population groups.

Barriers in the pedestrian environment do not simply function as either passable or impassable; rather, they can exhibit varying levels of passability, requiring different degrees of effort to overcome. In this context, *passability* refers to the extent to which a microscale street element can be traversed by individuals with different mobility capacities, as well as the level of effort required to do so. The level of passability associated with a given microscale street element depends on both its physical characteristics and an individual's mobility capacities.

Similarly, facilitators do not simply function as either facilitating or not facilitating mobility; instead, they can provide different levels of facilitation that support movement to varying degrees. The level of facilitation offered by a microscale street element reflects the extent to which it reduces the physical or navigational effort, difficulty, or constraints associated with moving through the environment, thereby enabling individuals with different mobility capacities to navigate pedestrian spaces more easily. For example, features such as kerb ramps, tactile paving, pedestrian signals, or available seating may substantially reduce mobility-related constraints for some individuals, while providing only limited additional support for others.

As a result of this variability in impact, the same microscale street element may be easily navigable for some individuals while posing significant challenges for others. These differences may occur between population groups with different impairments, but they can also arise within the same group due to variations in mobility capacities, as discussed earlier. Consequently, the effective passability of a barrier, or the level of facilitation provided by a facilitator, emerges from the relationship between the environmental demands imposed by the built environment and the mobility capacities of the individual encountering it.

Conclusion. The variations discussed throughout this subsection, including differences in individuals' mobility capacities, the diverse ways in which microscale street elements can function as barriers or facilitators, and the varying levels of passability and facilitation they may exhibit, illustrate the complexity of designing pedestrian environments that accommodate diverse mobility needs. Because individuals differ in their mobility capacities, the same environmental feature may produce different accessibility outcomes for different users, meaning that a single design intervention does not necessarily generate equal accessibility benefits across population groups. These considerations highlight that accessibility in pedestrian

environments is shaped not only by travel distance or network structure, but also by the relationship between individuals' mobility capacities and microscale street elements in the built environment.

1.3 Research gaps and research objectives

This thesis was conducted within the broader framework of the *Situation-Aware Individualised Spatial Accessibility Analytics (SISAL)* fellowship project funded by the Digitalization Initiative of the Zurich Higher Education Institutions (DIZH) and awarded to Dr. Hoda Allahbakhshi. SISAL aims to develop methods to generate individualised, context- and situation-aware accessibility profiles by combining open-access geographical and environmental data with mobile sensor data and advanced analytical approaches (University of Zurich, 2023). Within this context, the present study addresses key gaps in the conceptualisation and measurement of spatial accessibility.

Despite the field of accessibility research expanding considerably in recent decades, important limitations remain in how accessibility is conceptualised and measured, particularly regarding the integration of contextual factors that shape pedestrian mobility. Accessibility research predominantly focuses on the general population, often leading to assumptions of relatively homogeneous travel capabilities across individuals and reliance on shortest-path metrics and simplified network representations (Gharebaghi et al., 2021). While these approaches provide useful general insights, they are typically implemented at coarse spatial scales and tend to overlook how fine-grained features of the pedestrian environment, such as microscale street elements, interact with individuals' mobility capacities. Conversely, studies that explicitly account for such microscale elements are often limited to small study areas, such as university campuses or small town centres, constraining their ability to capture broader spatial patterns (Achuthan et al., 2010; Kasemsuppakorn & Karimi, 2009; Sobek & Miller, 2006; Tajgardoon & Karimi, 2015). As a result, existing accessibility analyses only partially capture the interaction between the built environment and individual mobility capacities.

In response to these limitations, a growing body of research has begun to investigate the role of microscale street elements in shaping spatial accessibility for different population groups. Some studies focus on the accessibility experiences of specific groups with distinct mobility needs (Achuthan et al., 2010; Beale et al., 2006; Campisi et al., 2021; Vale et al., 2017), while others conduct between-group comparisons to better understand how accessibility patterns vary across populations (Jehle et al., 2024; Lanza et al., 2023; Tajgardoon & Karimi, 2015). However, several challenges remain, particularly regarding how microscale street elements are identified, represented in spatial accessibility models, and measured and linked to individuals' diverse mobility capacities.

Against this background, the overarching aim of this thesis is:

> **Overarching Aim of the Thesis**
> Examine how contextual factors, specifically external environmental characteristics and internal individual mobility capacities, shape spatial accessibility, and how their impacts vary both between and within population groups with different mobility capacities.

The remainder of this section outlines the main research gaps addressed in this thesis and presents the four corresponding **research objectives (ROs)**.

1.3.1 RO1: Identify microscale street elements influencing spatial accessibility

To understand how microscale street elements influence the spatial accessibility of individuals with diverse mobility restrictions, it is first necessary to identify which elements shape accessibility for these groups.

Although a growing body of research acknowledges the importance of microscale street elements for spatial accessibility and seeks to identify which features matter for different users, research findings remain fragmented and dispersed across studies. Much of the literature concentrates on a limited set of population groups, most commonly wheelchair users (Beale et al., 2006; Kasemsuppakorn et al., 2015; Matthews et al., 2003; Meyers et al., 2002) and older adults (Achuthan et al., 2010; Wennberg, 2009), while comparatively few studies examine a broader spectrum of mobility capacities. Furthermore, studies typically examine different subsets of microscale street elements, thus limiting the comparability of findings across studies and hindering a broader understanding of which elements influence movement through urban environments for different population groups.

To address these shortcomings, the first research objective of this thesis is defined as follows:

> **RO1:** Systematically identify microscale street elements that influence spatial accessibility for different population groups and develop a comprehensive classification of these elements, including their reported effects and the frequency with which they are associated with different population groups in the literature.

1.3.2 RO2: Assess perceived impacts of microscale street elements

Building on the identification of relevant microscale street elements, understanding how these elements shape spatial accessibility requires assessing the extent to which they impede or facilitate movement at a fine-grained level, as well as how these effects vary both within and between population groups.

Empirical approaches such as questionnaires (Wazani et al., 2021), interviews (Rosenberg et al., 2013), and focus groups (Neven & Ectors, 2023) provide valuable insights into how individuals perceive and experience microscale street elements. Such methods can help identify whether particular features are experienced as barriers or facilitators and provide

insights into their perceived impacts on movement. However, many studies rely on simplified classifications, often categorising street elements in binary terms (i.e., as either barriers or not), even though their effects are typically more gradual in nature. In addition, studies that adopt more detailed assessments of subjective experiences related to microscale street elements frequently focus on a single population group (Bredmose et al., 2023; Li et al., 2025), limiting opportunities to systematically compare how individuals with different mobility capacities experience these elements.

Addressing these limitations leads to the second research objective of this thesis:

> **RO2:** Analyse empirically the between-group and within-group variation in the perceived severity and facilitative effects of microscale street elements across different population groups.

1.3.3 RO3: Enrich pedestrian networks with microscale street elements

Assessing how the interaction between individuals' subjective perceptions and microscale street elements shapes spatial accessibility patterns requires enriching pedestrian networks with detailed information on the precise locations and characteristics of these elements.

Recent developments in accessibility modelling increasingly recognise the needs of individuals with diverse mobility capabilities (Lid & Solvang, 2016; Vale et al., 2017). However, models that explicitly incorporate microscale street elements within pedestrian network representations remain scarce. Several studies have attempted to integrate such accessibility features into pedestrian networks (Achuthan et al., 2010; Jehle et al., 2024; Li et al., 2025; Tajgardoon & Karimi, 2015; Vale et al., 2017), but a widely adopted methodological workflow for systematically incorporating fine-grained, sidewalk-level accessibility data into network representations is still lacking. Existing approaches often rely on simplified assumptions, such as only indicating whether a barrier or facilitator is present along a network segment (Achuthan et al., 2010; D'Orso & Migliore, 2020), estimating the minimum clear width of sidewalks based on obstacle location and size (Vale et al., 2017), or using aggregated accessibility indicators (D'Orso & Migliore, 2020; Hwang, 2022). These representations limit the ability to analyse the impact of microscale street elements individually or by type, and to link these features to the heterogeneous mobility capacities of different users.

This research gap inspired the third research objective of this thesis:

> **RO3:** Develop and implement a methodological workflow that integrates microscale street elements into pedestrian network representations, thereby enriching pedestrian networks with detailed accessibility information.

1.3.4 RO4: Model the impact of microscale street elements and individuals' subjective perceptions on accessibility patterns

Identifying microscale street elements and understanding individuals' subjective perceptions of them do not, in themselves, reveal how these factors shape spatial accessibility patterns. To assess their broader implications, it is necessary to integrate both built environment characteristics and perception-based evaluations into spatial accessibility models and examine how resulting accessibility outcomes differ between population groups.

Several studies have incorporated microscale street elements into spatial accessibility models (Achuthan et al., 2010; Šakaja et al., 2019; Vale et al., 2017). In many cases, however, their impacts were assessed only with respect to one population group, meaning these approaches rarely account for how individuals with different mobility capacities perceive and experience such elements. To address this limitation, other studies attempted to differentiate the impact of microscale street elements across population groups and assess potential accessibility disparities (Jehle et al., 2024; Lanza et al., 2023; Tajgardoon & Karimi, 2015). However, these models typically rely on weights derived from the literature rather than empirical perception data (Jehle et al., 2024; Tajgardoon & Karimi, 2015). Consequently, they provide only limited insight into how the perceived severity or facilitative effects of microscale street elements translate into differentiated spatial accessibility outcomes.

Empirical perception studies remain relatively limited. Few studies have examined how microscale street elements interact with individuals' mobility capacities while drawing on users' perception data (Li et al., 2025), and those that do typically focus on a single population group. This restricts the ability to compare how the impacts of these elements translate into differing spatial accessibility patterns across groups.

These shortcomings prompted the fourth research objective of this thesis:

> **RO4:** Assess how microscale street elements and individuals' subjective perceptions influence the spatial accessibility of individuals with different mobility capacities, and how these differences shape overall patterns of spatial accessibility.

1.4 Population groups considered and study area

1.4.1 Population groups

To investigate how contextual factors influence spatial accessibility, this thesis draws on the *ZüriACT: Zürich Accessible CiTy project*, which provided the spatial data used in the analysis (Allahbakhshi & Ardüser, 2024; Allahbakhshi et al., 2026), and focuses on four population groups:

- **Mobility-impaired individuals**, defined as individuals with physical impairments that affect their ability to move or walk.
- **Older adults aged 65 and above**, who may experience mobility restrictions associated with ageing.
- **Situationally restricted individuals**, referring to individuals who are not generally

mobility restricted but may experience temporary mobility constraints in certain situations, such as caregivers accompanying a wheelchair user, parents with strollers, or individuals carrying large luggage items.
- **Visually impaired individuals**, referring to individuals experiencing partial or complete vision impairment.

While this thesis focuses on multiple population groups that experience mobility restrictions or impairments, not all chapters analyse all groups. Chapters 2 and 3 consider all four groups, Chapter 4 develops a methodological framework independent of specific user groups, and Chapter 5 focuses specifically on mobility-impaired and visually impaired individuals.

1.4.2 Study area

The empirical components of this thesis are conducted at different spatial scales depending on the research objective. Chapter 2 consists of a systematic literature review and is therefore not restricted to a specific geographical context. Chapter 3 analyses survey responses from residents of Switzerland, enabling examination of differences in perceptions across population groups at the national level. Chapters 4 and 5 focus on a detailed case study in District 1 of the City of Zurich (Figure 1.1), aimed at developing and applying the methodological framework for modelling spatial accessibility. This case study area was selected due to the availability of fine-grained spatial data on pedestrian infrastructure and microscale street elements, collected as part of the *ZüriACT* project (Allahbakhshi & Ardüser, 2024; Allahbakhshi et al., 2026). Chapters 4 and 5 provide more detail regarding this study area.

1.5 Thesis structure and overview

1.5.1 Structure of the thesis

The main body of this thesis consists of four research papers, presented as Chapters 2 to 5 and organised around the four research objectives (Figure 1.2). The chapters follow a clear progression: beginning with the identification of relevant microscale street elements by means of a review of the literature (Chapter 2); then examining how their effects are experienced by individuals with different mobility capacities (Chapter 3); followed by the development of an enriched pedestrian network that integrates fine-grained accessibility data (Chapter 4); and finally applying this framework to assess spatial accessibility patterns (Chapter 5). The thesis concludes with Chapter 6, which provides an overall synthesis, including a discussion of the main findings and contributions in relation to the research objectives, their implications for practice, the study's limitations, and directions for future work.

1.5.2 Overview of thesis chapters

Chapter 2 presents a systematic review of the literature examining how microscale street elements influence spatial accessibility for different population groups, particularly individuals with mobility restrictions. The chapter identifies and categorises street elements according to their facilitating or impeding role, the population groups affected, and the frequency with which they are reported in the literature. Based on this synthesis, the chapter provides a structured overview of current knowledge on factors influencing spatial accessibility, identifies key research gaps, and outlines directions for future research, serving as a foundation for the following chapters.

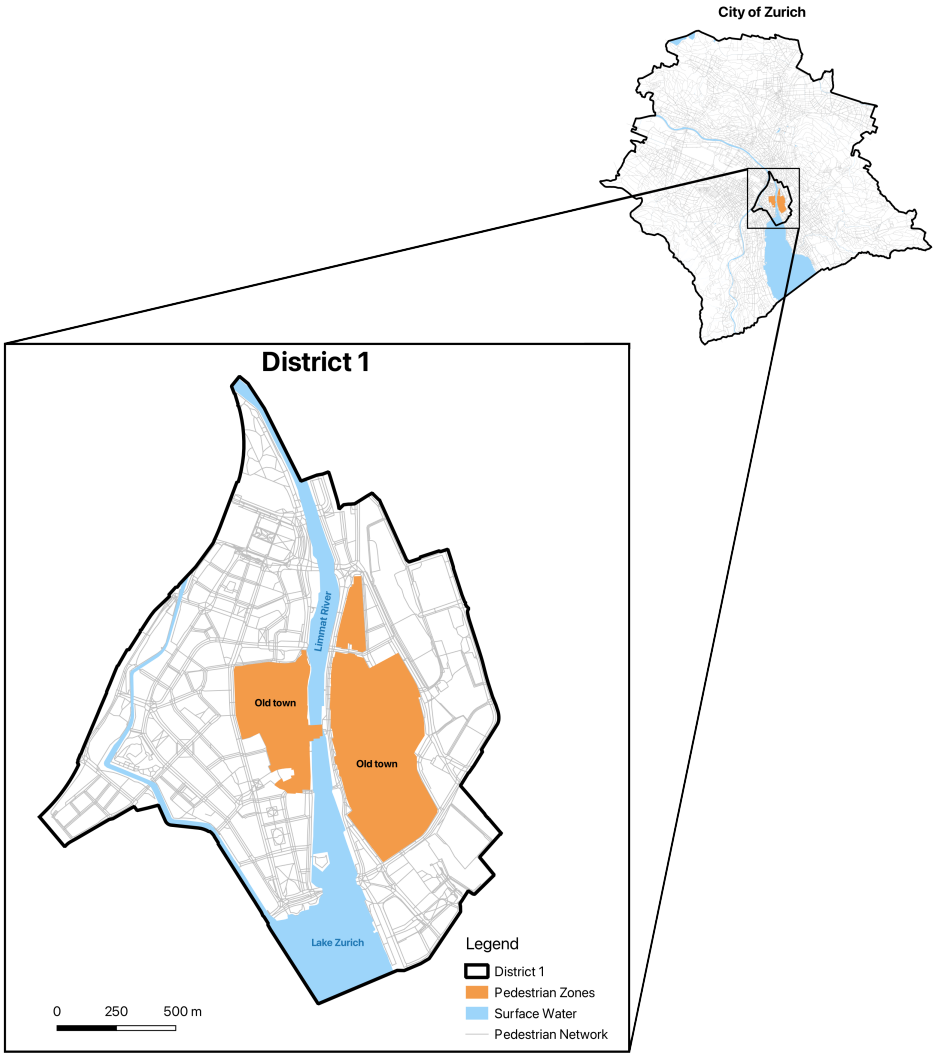


Figure 1.1: Overview of the study area for Chapters 4 and 5, District 1 of the city of Zurich.

Chapter 3 reports the results of an empirical study that quantifies how individuals with heterogeneous mobility capacities perceive the severity or facilitating impact of microscale street elements in their daily mobility. Building on the elements identified in Chapter 2, the study analyses differences in perception across the four population groups mentioned in Section 1.4.1 and examines both between-group and within-group variation associated with individual characteristics.

Chapter 4 develops a methodological workflow for integrating microscale street elements into pedestrian network data to support fine-grained spatial accessibility assessments. The chapter presents procedures for linking accessibility data from multiple sources with pedestrian networks and for deriving impedance measures that reflect the impact of microscale street elements on movement. The resulting framework provides the technical foundation for assessing spatial accessibility for different individuals and forms the basis for incorporating subjective perception data in Chapter 5.

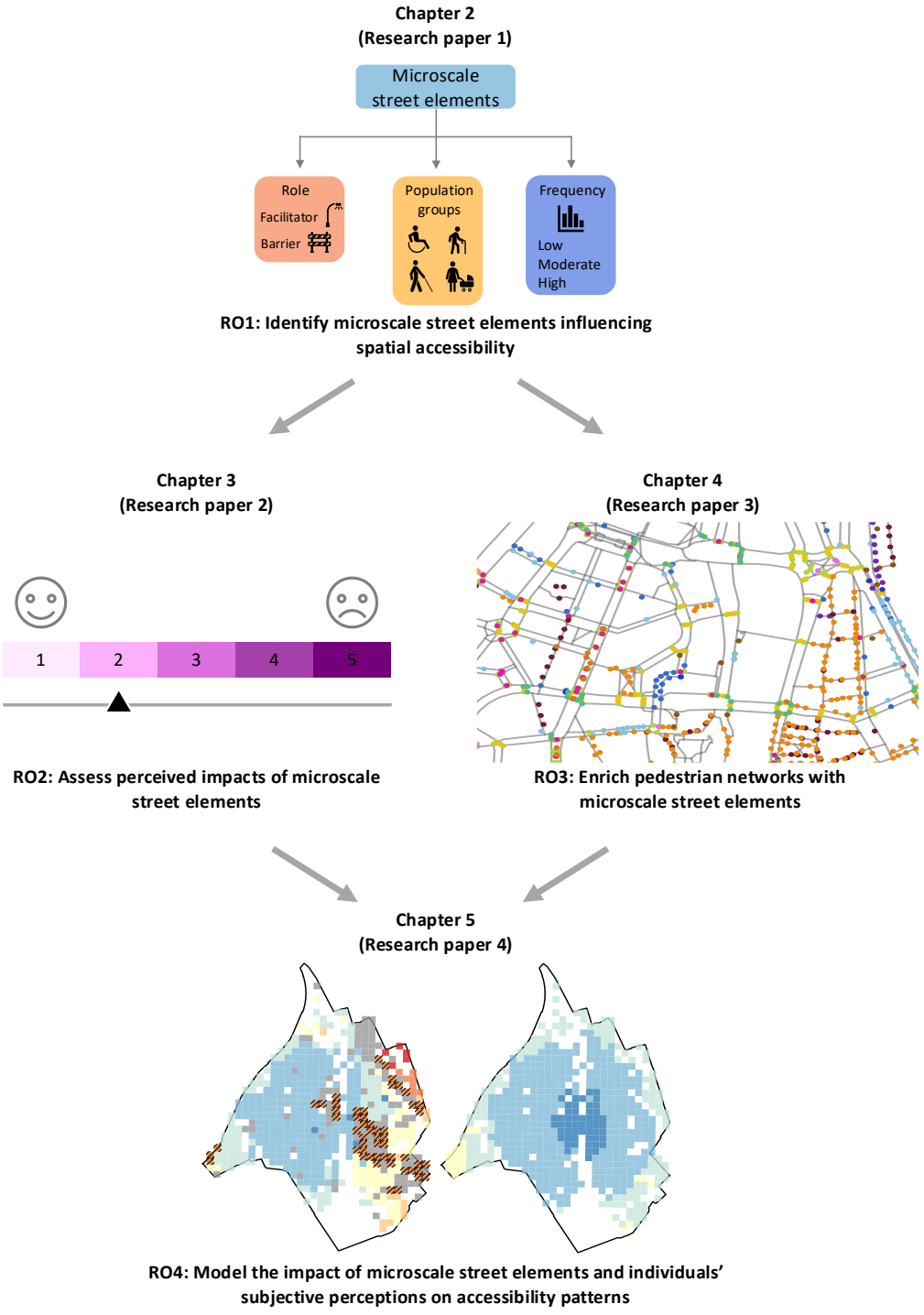


Figure 1.2: Overview of the thesis structure, mapping the four research objectives (RO1–RO4) to their respective chapters and research papers, and showing the logical progression from Chapter 2 through to Chapter 5.

Chapter 5 builds on the methodological developments and empirical findings of the previous chapters to model how internal and external factors jointly shape spatial accessibility patterns across population groups. By combining perception-based weights derived from the empirical analysis in Chapter 3 with the enriched pedestrian network developed in Chapter 4, the chapter presents a framework for assessing differences in spatial accessibility at a fine-grained spatial scale.

Chapter 6 synthesises the findings of the preceding chapters by integrating the conceptual, empirical, and methodological insights developed throughout the thesis. It begins with a structured summary of the main findings of each chapter in relation to the research objectives. Building on this, the chapter identifies key overarching insights regarding how microscale street elements and heterogeneous mobility capacities shape pedestrian accessibility. It then discusses the implications of these insights for both research and planning practice, followed by a reflection on the main limitations of the thesis. The chapter concludes with an outlook on directions for future research.

1.5.3 Related publications

Each of the Chapters 2 to 5 is adapted from one research paper that has been published or submitted to recognised scientific journals or international

- **Chapter 2, based on Research Paper 1:**
  Georgescu, A. I., Allahbakhshi, H. & Weibel, R. (2024). The impact of microscale street elements on active transport of mobility-restricted individuals: A systematic review. *Journal of Transport & Health*, 38, 101842. https://doi.org/10.1016/j.jth.2024.101842
- **Chapter 3, based on Research Paper 2:**
  Georgescu, A.I., Allahbakhshi, H., Darvishy, A., & Weibel, R. (under review). Same sidewalk, different experiences: How mobility restrictions shape perceptions of urban pedestrian infrastructure and accessibility. *Travel Behaviour and Society.*
- **Chapter 4, based on Research Paper 3:**
  Georgescu, A. I., Allahbakhshi, H., & Weibel, R. (2025). Developing enriched pedestrian networks using accessibility features. *AGILE GIScience Series*, 6, 23. https://doi.org/10.5194/agile-giss-6-23-2025
- **Chapter 5, based on Research Paper 4:**
  Georgescu, A. I., Allahbakhshi, H., Harrafamoughin, A., & Weibel, R. (2026). Mind the obstacle: Impact of microscale street elements on urban accessibility disparities. *Journal of Urban Mobility*, 9, 100203. https://doi.org/10.1016/j.urbmob.2026.100203

2

Microscale street elements influencing spatial accessibility

Chapter Outline

This chapter is adapted from the following publication:

Georgescu, A. I., Allahbakhshi, H., & Weibel, R. (2024). The impact of microscale street elements on active transport of mobility-restricted individuals: A systematic review. *Journal of Transport & Health*, 38, 101842. https://doi.org/10.1016/j.jth.2024.101842

Supplementary material can be found in Appendix A.

Scope: Identify and classify microscale street elements influencing spatial accessibility across population groups, based on their reported effects and frequency in the literature.

Approach:

- Conducted a systematic review of three databases: Scopus, Web of Science and PubMed.
- Analysed 20 eligible studies on perceptions of microscale street elements by mobility-restricted individuals.
- Extracted data on target population groups, data collection methods used and reported microscale street elements.
- Classified microscale street elements as barriers or facilitators and assessed how frequently they were mentioned across the included studies and population groups.

Key insights:

- The impact of microscale street elements varies with individuals' mobility capacities, as certain elements can act as both barriers and facilitators.
- Most studies focus on individual population groups, limiting a comprehensive understanding of how mobility capacities shape interactions with microscale street elements.
- Studies predominantly rely on qualitative methods (e.g. interviews, focus groups, questionnaires), with different approaches capturing complementary aspects of individuals' interactions with the built environment.
- Diverse mobility capacities make achieving universal design challenging.

Contributions of the PhD candidate: The PhD candidate designed and executed the literature search, screened and reviewed all retrieved records to identify the initial set of eligible manuscripts, and conducted the full-text review, synthesis, and critical evaluation of the included studies. The PhD candidate also drafted the manuscript.

CRediT Authorship Roles: Alexandra-Ioana Georgescu: Conceptualisation, Methodology, Formal analysis, Investigation, Writing – original draft, Writing – review & editing. Hoda Allahbakhshi: Conceptualisation, Methodology, Writing – review & editing, Supervision, Funding acquisition. Robert Weibel: Conceptualisation, Methodology, Writing – review & editing, Supervision, Funding acquisition.

2.1 Introduction

The anticipated global shift towards urban environments, with 68% of the world's population expected to reside in urban areas by 2050 (United Nations, 2019), coupled with the expected doubling of the worldwide population over 65 from 9% in 2019 to 16% in 2050 (United Nations, 2021) and with an increase of people experiencing mobility-restricting impairments, calls for a renewed consideration of the accessibility and social inclusion of urban spaces (World Health Organization, 2015). People with different mobility restrictions encounter numerous barriers that hinder their mobility in urban environments, thus making certain areas or services inaccessible (Hammel et al., 2015), which in turn can potentially lead to social exclusion (Svensson, 2010). This is especially important since 16% of the world's population lives with significant disabilities (World Health Organization, 2022), impairments that can impact their movement through space. With these facts and trends in mind, there is a clear need to assess and adapt our cities to create more inclusive environments and eliminate accessibility bias (i.e., an unequal possibility of interacting with the physical and social environment).

Reducing inequalities, focusing on the well-being of all individuals, and constructing more inclusive and sustainable cities are essential targets included in the Sustainable Development Goals (SDG) 3, 10, and 11 published by the United Nations (2022). While sustainability initially focused on environmental concerns, it has evolved to also include the social dimension, considering the social equity and the quality of life of individuals (Dempsey et al., 2011). Furthermore, literature highlights the importance of resilient cities – cities that can adapt and respond to different shocks such as natural disasters, economic crises, population growth or rapid demographic shifts (Desouza & Flanery, 2013). Social resilience, which is concerned with the overall well-being of individuals, can be fostered and improved by working to reduce social isolation (Martin, 2015). Improving pedestrian infrastructure is one strategy to promote this resilience and enhance city sustainability, eliminating dependencies of individuals on vehicles or other individuals, while at the same time reducing social isolation and improving the physical and mental health of individuals. However, pedestrian infrastructure has been largely overlooked (Rhoads et al., 2023), leading to various challenges associated with sidewalks, such as their poor condition and maintenance, street furniture blocking the path, or sidewalks not existing altogether. These issues not only hinder individuals' movement (Núñez et al., 2022), but also jeopardise the road safety of pedestrians (Corazza et al., 2016).

Going more into detail, microscale street elements are more significant factors for pedestrians' satisfaction with walking when compared to mesoscale factors such as land use diversity and street density (Bivina et al., 2020). Microscale street elements are details of the built environment belonging to sidewalks, crosswalks, or pedestrian areas that can be represented by sidewalk material (e.g. cobblestones) and condition (e.g., cracks, manholes), by street furniture (e.g., benches, utility panels, bollards), by height difference elements (e.g., stairs, ramps), by crosswalk infrastructure (e.g., kerb ramps, visual and audio signals) or by design characteristics (e.g., architectural structures limiting the width or height of the sidewalk) (Millstein et al., 2013). Furthermore, several studies have shown the negative impact that different microscale street elements and the lack of pedestrian infrastructure have on the movement through the urban environment of people with different mobility restrictions

(Achuthan et al., 2010; Bhuiya et al., 2024; Lid & Solvang, 2016; Mao & Chen, 2022; Mohiuddin et al., 2024; Orellana et al., 2020; Vale et al., 2017). Ramps with steep slopes and uneven surfaces full of cracks force individuals with mobility restrictions not only to depend on the support offered by other individuals, such as family members, but also to rely on more expensive travel modes than they would otherwise choose (Bhuiya et al., 2022). Moreover, studies have shown that the risks of pedestrian accidents are notably higher for pedestrians with some form of disability when compared to individuals with no disability (Schwartz et al., 2022). Older adults with declining mobility capacities are more likely to have a pedestrian fall-related injury that involves a sidewalk microscale element such as kerbs (Naumann et al., 2011). Thus, their perceptions of the built environment and how this should be changed could provide valuable insights and critically inform city and infrastructure design.

Spatial accessibility (or short: *accessibility* in this article) refers to how easily different opportunities can be reached from a certain geospatial location through movement in physical space, taking into consideration the spatial distribution of activities, the abilities of the individuals, and their desires (Hansen, 1959). There is a plethora of contextual factors that can influence spatial accessibility, starting from internal ones, such as personal mobility capacities, and ending with external ones, such as the built environment (Lid & Solvang, 2016), weather conditions, or attractiveness and comfort of the urban design (Ortega et al., 2021). What represents an obstacle for a particular individual on a particular day may not restrict another individual or the same individual under different conditions. For an accurate representation, the skillset and capacities that an individual has in order to make use of the accessible opportunities have to be considered. However, this skill set must also be matched by the surrounding environment. Combined with the mobility capacities, the existing street elements in the built environment can impede or facilitate movement for individuals.

There is a vast body of literature that studied the effects of microscale street elements on the accessibility of mobility-restricted individuals (Beale et al., 2006; Gharebaghi et al., 2018; Matthews et al., 2003; Meyers et al., 2002; Orellana et al., 2020; Sobek & Miller, 2006; Wennberg, 2009). When encountered in the urban environment, such a microscale element can become a physical barrier and cause an individual to slow down, take an alternative route, or halt completely. Examples of how internal and external factors can impact spatial accessibility are: wheelchair users not being able to use narrow sidewalks (Kasemsuppakorn & Karimi, 2009); visually impaired people struggling with making their way through news-stands, advertisements and tables on the sidewalk (Lid & Solvang, 2016); or older adults experiencing fatigue faster and having no seats available to rest (Koon et al., 2020). The presence of barriers to mobility can impact both the physical and mental health of mobility-restricted individuals, decreasing their participation in social life (Gamache et al., 2019) and increasing their feelings of loneliness (Lid & Solvang, 2016; Portegijs et al., 2020; Rantakokko et al., 2014).

The interplay between internal and external factors when discussing individuals' movement through space is still not fully understood, especially when considering microscale street elements. This can have critical implications, for example, policies and regulations not addressing frequently encountered barriers by mobility-restricted individuals (Wennberg, 2009). While the mapping review of Gamache et al. (2019) summarises the accessible features that different sidewalk elements exhibit in the included literature, there is insufficient information to understand what the characteristics of the microscale street elements are that hinder or facilitate spatial accessibility and how they differ with different mobility capacities.

Although the fields of accessibility and urban planning are considerably broad, few studies consider between- and within-group heterogeneities when performing accessibility assessments or when designing public pedestrian spaces. Most studies that focus on the impact of microscale elements on the accessibility of different individuals (Achuthan et al., 2010; Beale et al., 2006; Kasemsuppakorn et al., 2015; Matthews et al., 2003; Wennberg et al., 2009) as well as recent review articles that have discussed the impact that the built environment has on the social participation and accessibility of individuals (Figueiredo et al., 2023; Kapsalis et al., 2024; Townsend et al., 2021) consider only one population group. This makes the conclusions and design recommendations drawn from such studies susceptible to error, as they could negatively impact the accessibility of individuals not included in these studies.

Therefore, there is a need to study the perceptions of individuals with varying mobility capacities of the built environment, focusing on between- and within-group heterogeneities, to understand how various street elements shape spatial accessibility more accurately and how the needs of different individuals overlap or contradict. By systematically analysing and comparing the related literature, we seek to provide a comprehensive overview across various population groups. This will lead to relevant insights that will allow us to make recommendations on how sidewalk accessibility in the urban environment can be adjusted to fit the needs of all population groups. A more inclusive pedestrian infrastructure can lead to an increase in active mobility, which, in turn, can lead to improved levels of physical health and well-being of individuals. Furthermore, the findings of this review can inform city planning and design, as well as simulation models of planning and intervention scenarios using microsimulation or agent-based models.

2.2 Methodology

2.2.1 Research questions

The aim of this systematic literature review is to provide a comprehensive and structured state of knowledge concerning internal and external factors that impact spatial accessibility in urban areas. For each of the studies identified by the methodology described below, the following research questions are answered:

1. What are the characteristics of the participants who took part in the spatial accessibility related studies?
2. What methods are used to capture different individuals' perceptions of the street elements present in the urban environment?
3. How do different population groups perceive the street elements in the urban environment?
4. What is the frequency with which the street elements are mentioned?

2.2.2 Literature search

Based on discussions with leading experts and already existing literature, we used the following query: (*"differently abled" OR "physical* disab*" OR "mobility disab*" OR "mobility restrict*" OR "mobility impair*" OR "mobility limit*" OR "visual disab*" OR "visually impair*" OR blind OR "older adults" OR "older people" OR "older population" OR elderly OR "mobility aid*" OR wheelchair**) AND (*sidewalk* OR footpath* OR pathway* OR pavement* OR "built environment" OR barrier* OR facilitator**) AND (*accessibility OR walkability*) AND NOT (*patient* OR rehab**), to search for articles in three different databases, Scopus, Web of Science and PubMed. The search was applied to the title and abstract of the documents.

2.2.3 Eligibility criteria

The main selection criteria when screening the documents were that the study must have focused on urban areas and considered at least one street element of interest, and the perception of at least one target population group regarding it. Other inclusion criteria were:

- Journal articles published between 2012 – 2022 in English. Other review articles were excluded.
- Studies including participants older than 18 years old.
- Studies including real-world data.

Studies focusing on developing mobility aids or focusing exclusively on public transport and its associated facilitators and barriers were excluded. The reason behind this is that public transportation has a different set of elements that can impede or facilitate the movement of individuals, such as the attitude of the driver, the attitude of other people present, inaccessible stops, gaps or steps to the vehicle, narrow spaces in the vehicle, lack of handrails and accessible seating, sudden brakes and acceleration, etc. (Bezyak et al., 2017; Fasina et al., 2020; Mogaji et al., 2023; Mwaka et al., 2024). Furthermore, studies that usually focus on public transportation only mention generally that the poor condition of the sidewalk to reach the stops impedes their mobility, however, without further specifying specific sidewalk microscale elements (Fasina et al., 2020), which are the focus of this study.

2.2.4 Article selection

The complete workflow used to select the articles included in this review is summarised in Figure 2.1. A total of 2782 candidate articles were identified: 1036 from Scopus, 1347 from Web of Science, and 399 from PubMed. After removing duplicates, 1765 articles remained. The titles and abstracts of these 1765 articles were screened based on the main inclusion criteria, after which 248 articles remained. For these 248 articles, the whole text was screened, taking into consideration all inclusion criteria, and in the end, 20 articles were included: 14 from Scopus and 6 from Web of Science. Zero articles were included from the PubMed database.

While studies focusing exclusively on accessibility by public transport were excluded, the paper by Park and Chowdhury, 2018, which focused on the participants' typical journey by public transit, was still included, as it examined the "door-to-door" journey, also considering

the trip to and from the public transport stop through the environment. Furthermore, all included studies focused on urban environments; however, one paper included both rural and urban environments (Aldersey et al., 2018). As the authors did not distinguish between the two areas, and the barriers and facilitators observed in that study were in accordance with all other included studies, the study was considered for this review.

2.2.5 Data extraction

While assessing the included articles, data regarding four main features were extracted for each study, and summarised in a spreadsheet: the participants and their characteristics, documenting key factors such as the type of mobility restrictions, the type of mobility assistive devices, the sample size and the age groups (RQ 1); the data collection methodologies used to collect the participants' perception of street elements in the built environment (RQ 2); the street elements mentioned in the studies together with their characteristic as a barrier or facilitator for each population group (RQ 3); and the frequency with which the street elements were mentioned across the selected studies was manually counted (RQ 4). As several studies focused on more than one population group, a study mentioning one element can be counted multiple times if individuals from multiple population groups mentioned the respective microscale street element as a barrier or facilitator.

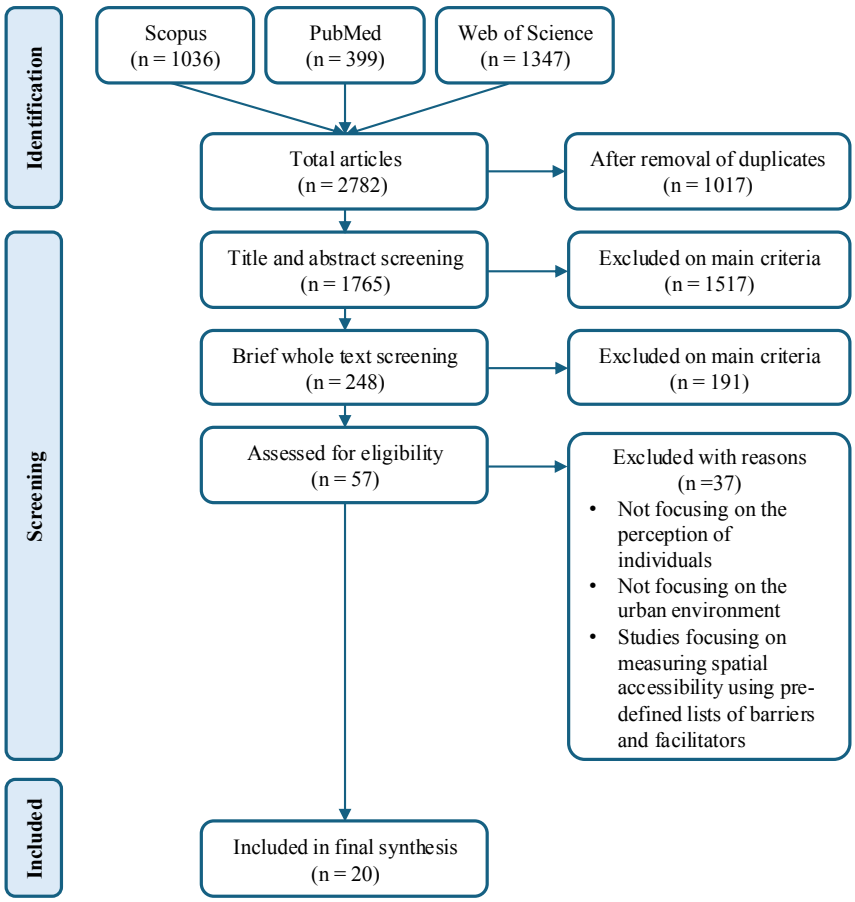


Figure 2.1: Flow diagram of the systematic review process.

2.3 Results

The 20 articles examined in this study were conducted in various locations across the globe. The highest number of studies (n = 7, 35%) were conducted in North America, specifically in countries like the United States, Mexico and Canada. In Europe, the included studies (n = 4, 20%) took place in Belgium, Italy, Croatia, and Ireland. The remainder of the studies concentrated on South America (n = 2, 10%), focusing on Ecuador and Chile; on Asia (n = 4, 20%), focusing on China, Malaysia, Taiwan, and South Korea; and in Oceania (n = 1, 5%) in New Zealand. It is important to note that spatial accessibility is highly contextual, and infrastructure in urban environments can vary significantly between countries. However, considering the wide range of locations covered in the articles, they can be assumed to collectively provide a comprehensive overview.

2.3.1 Participants and their characteristics

Sample size and age groups: The sample size chosen to conduct the included studies varies greatly, with seven studies including less than 20 participants, eight studies between 20 and 60 participants, and five studies with more than 60 participants. The smallest sample size was used in the study of Cushley et al., 2022, where the perception of three visually impaired people was recorded. The largest sample size of 385 participants was recorded in the study of Harris et al., 2015, which used a web-based survey to capture the differences in the difficulty level of 50 barriers that wheelchair users encounter in the environment. Regarding the age range of the participants, five of the studies included adults of all ages, three of the studies included younger adults only (i.e., below 65 years old), eight of the studies included older adults, and four of the studies did not specify the ages of their participants. It can be observed that, apart from the studies focusing on older adults, the rest did not target a specific age group and focused more on mobility restrictions and assistive device use when selecting participants.

Type of mobility restrictions: Although the keywords used to search for articles included specific target population groups, this review focuses more on the diversity of individuals included in the eligible studies and how individuals were categorised. The participants of the included studies were divided into four main groups: mobility-impaired individuals (MI), visually impaired individuals (VI), older adults (OA), and individuals with situational mobility restrictions, i.e., individuals using strollers (SMR). Individuals with situational mobility impairments are individuals who find themselves in a temporary situation, and, as a result, their mobility is restricted; otherwise, it would not be. This may include people who had an accident and have now their mobility restricted or may include parents with pushchairs and caregivers. Although the individuals themselves are not mobility restricted, because of having a pushchair, for example, it becomes more important if there exist kerb ramps at crosswalks; the presence of stairs can make that segment completely inaccessible, or a steep sidewalk could make pushing the stroller quite difficult. Furthermore, being a caregiver, for example, helping a family member by pushing their wheelchair, can be physically demanding (Bhuiya et al., 2022), and thus, the caregiver also becomes susceptible to the barriers the wheelchair user experiences. Table 2.1 shows what population groups are included in each respective article. The majority of papers, 15 out of 20, focus on only one

population group, with only two articles portraying the perception of a variety of individuals (Han et al., 2020; Wazani et al., 2021), including three different population groups. Both articles also include individuals with hearing impairments, which are outside the scope of this review.

Table 2.1: Population groups included in the studies. (MI – mobility-impaired; OA – older adults; VI – visually impaired individuals; SMR – individuals with situational mobility restriction; HI – hearing-impaired individuals)

References	**Population Group**
Wazani et al., 2021	MI, VI, OA
Han et al., 2020	MI, VI, SMR
Park and Chowdhury, 2018	MI, VI
Orellana et al., 2020	MI, SMR
Aldersey et al., 2018; Harris et al., 2015; Prescott et al., 2021; Rosenberg et al., 2013; Šakaja et al., 2019	MI
Chen et al., 2015; Gao and Nagai, 2021; Herrmann-Lunecke et al., 2022; Klicnik and Dogra, 2019; Ottoni et al., 2016; Van Cauwenberg et al., 2014	OA
Campisi et al., 2021; Cushley et al., 2022; Jenkins et al., 2015; McMullan and Butler, 2019; Rey-Galindo et al., 2020	VI

Type of mobility assistive devices: To move independently through the environment despite their restrictions, individuals frequently make use of mobility assistive devices. As these devices differ in size, characteristics, and functionality, certain street elements will be perceived differently depending on the device used. While a slight incline of the sidewalk may not pose a barrier for someone using a powered wheelchair, it can significantly impede an individual using a manual wheelchair due to the increased effort required, thus creating a barrier. Therefore, the mobility-impaired individuals' group can be further categorised as manual wheelchair users (MWC), powered wheelchair users (PWC), scooter users (S) and users of walking assistive devices (WAD), such as walkers, rollators, crutches or walking sticks. For the studies where it was not clear if the participants were using a manual or powered wheelchair, the authors of the studies were contacted and asked. For the study of Park and Chowdhury (2018), the authors were not interested in whether the participants were using either a manual or a powered wheelchair and thus, it was assumed that both devices were used. Further, in the study of Wazani et al. (2021), the authors did not differentiate between the barriers perceived by manual or powered wheelchair users and thus, all barriers mentioned were assumed to apply to both categories. The study of (McMullan & Butler, 2019) studied the perception of visually impaired scooter users, and upon inspecting the discussed street elements and perceptions, they were categorised along with the visually impaired individuals.

Figure 2.2 summarises the exact classification of the mentioned population groups present in the eligible studies, together with the number of studies they are included in. The most frequently used assistive devices were found to be the manual and powered wheelchairs. Only two studies reported participants using walkers, rollators, crutches, walking sticks or canes (Park & Chowdhury, 2018; Rosenberg et al., 2013). Further, in the study of Rosenberg et al. (2013), participants also reported using non-conventional mobility assistive devices such as rocker-soled shoes, a bicycle, a guide dog, and a specially adapted walker.

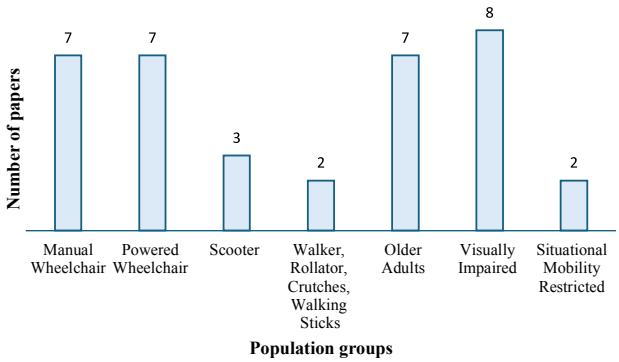


Figure 2.2: Number of studies that included a particular population group. Note that the first four groups are sub-groups of mobility-impaired individuals (MI).

2.3.2 Data collection methods

The data collection methods used in the included studies are summarised in Table 2.2. Overall, most of the studies relied on using qualitative data collection methods to understand how individuals perceive the built environment and how it affects their mobility abilities. Although most studies used interviews for data collection, methods such as questionnaires and focus groups were also used to elicit individual perceptions. When using web-based questionnaires, tools such as Survey Monkey or Survey Gizmo were used to ask participants either open-ended questions (Jenkins et al., 2015) or closed-ended ones (Harris et al., 2015), regarding participants' experience in the environment and the difficulty level of different street elements. For focus groups, depending on the number of participants, studies either conducted one focus group (Šakaja et al., 2019), or multiple (Klicnik & Dogra, 2019). When multiple focus groups were conducted, the groups formed were homogenous in terms of participants' characteristics, considering not only mobility restrictions but also their cultural and socioeconomic backgrounds, to allow for a more comprehensive understanding of the perceptions of each group (Klicnik & Dogra, 2019). For capturing detail, most studies relied on a mixed-methods approach, examples including combining sit-down and walk-along interviews, combining focus groups and field studies, or combining sit-down interviews and field studies.

The most frequently used data collection method was *interviews*, with 12 out of 20 included studies conducting various types of interviews. Some studies combined *sit-down* and *walk-along* interviews, not only to collect different types of data but also to be able to include more participants, as walk-along interviews may prove challenging for mobility-restricted individuals. Further, during *sit-down* interviews, multiple tools were used for data collection apart from questionnaires, such as *activity mapping* (Han et al., 2020) and *manipulated images* (Gao & Nagai, 2021; Van Cauwenberg et al., 2014). In studies using walk-along interviews, participants were asked to comment about walking and the aspects that facilitate or hinder its practice while the researchers observed the participants' behaviour during walks. Through *walk-along* interviews, researchers could obtain contextualised perspectives by walking (or wheeling, in some cases) through the environment with the participants, observing their behaviour and asking them questions about their decisions and experiences

Table 2.2: Summary of the data collection methods used to capture individuals' perception of the built environment concerning their spatial accessibility.

Method		**References**
Interview	Sit-down and walk-along	McMullan and Butler, 2019; Ottoni et al., 2016; Rosenberg et al., 2013
	Sit-down	Aldersey et al., 2018; Chen et al., 2015; Cushley et al., 2022; Han et al., 2020; Park and Chowdhury, 2018; Rey-Galindo et al., 2020; Van Cauwenberg et al., 2014
	Walk-along	Campisi et al., 2021; Herrmann-Lunecke et al., 2022; Prescott et al., 2021
Questionnaire	In person	Wazani et al., 2021
	Web-based	Gao and Nagai, 2021; Harris et al., 2015; Jenkins et al., 2015
Focus group		Klicnik and Dogra, 2019; Šakaja et al., 2019
Field study		Han et al., 2020; Orellana et al., 2020; Šakaja et al., 2019

in the moment. Further, these interviews were usually participant-led, with the researcher exerting minimal intervention. Regarding the routes chosen for the interviews, in most studies, participants were free to choose the route they wanted to travel, being prompted to select a familiar route (Herrmann-Lunecke et al., 2022; McMullan & Butler, 2019; Ottoni et al., 2016). Conversely, in the study of Prescott et al. (2021), the researchers chose the routes beforehand to maximise the variety of routes and street elements encountered.

A small number of included works also conducted *field studies*, where researchers not only collected the perception of individuals on different street elements but also their location in the environment, being able to create different maps related to the accessibility of the study area. Han et al. (2020) conducted an observation experiment where participants were free to move between a predefined origin and destination to examine the interactions between the participants and the built environment. Furthermore, Orellana et al. (2020) and Šakaja et al. (2019) conducted field assessment studies where study participants were asked to evaluate street segments individually, record barriers present and judge the accessibility of the segments.

2.3.3 Street elements

The included studies mentioned numerous street elements that impact participants' spatial accessibility and active mobility, which were grouped and aggregated and are presented in Table A.1 and Table A.2 in Appendix A. Note that even if different studies used different terms for the same element, the street elements were grouped based on their meaning under an umbrella term. For example, the term *kerb* is used as a synonym for curb, and the term *lowered kerb* is used as a synonym for dropped kerb, kerb ramp or curb cut.

2.3.3.1 Barriers

Table A.1 shows that the movement through space is hindered in different ways by different street elements for individuals belonging to distinct population groups. However, there is some overlap between the groups. Elements such as narrow or steep sidewalks, stairs, and permanent obstacles such as tree roots or overgrown vegetation are perceived as barriers by all groups. Nonetheless, some barriers are specific for certain population groups, such as having low headroom because of tree branches or low-lying objects, and no high contrast between the sidewalk and the street for visually impaired individuals; having the sidewalk paved with cobblestones or pavers that are either rough or have large uneven joints for mobility-impaired individuals; hard sidewalk materials for older adults; and drain grates for individuals that use wheeled mobility assistive devices. The individuals who use a powered wheelchair and the visually impaired individuals were the groups that mentioned the most barriers across all included studies. In contrast, the individuals who experience situational mobility restrictions, such as parents with pushchairs, mentioned the least barriers.

Additionally, Table A.1 shows that given the wide range of mobility capacities, some barriers may reveal a twofold effect, that is, the different characteristics of the same street element can make it a barrier or a facilitator, respectively, for different population groups. For example, the height of a kerb is a barrier for wheelchair users as it makes it challenging to traverse the kerb, and the wheels of the wheelchair can get stuck (Aldersey et al., 2018; Harris et al., 2015; Rosenberg et al., 2013; Šakaja et al., 2019; Wazani et al., 2021). However, visually impaired individuals prefer high kerbs and perceive lowered kerbs as barriers, as they use the height of the kerb for navigation to sense the end of the sidewalk (Han et al., 2020). Furthermore, this effect of street elements can also be observed between individuals who belong to the same group. In some studies, older adults state that sidewalks with softer surfaces, such as rubber tiles, represent a barrier and limit their spatial activity as they are too soft and unstable to walk safely (Chen et al., 2015). In comparison, in other studies, older adults state that harder surfaces represent a barrier as they have a greater impact on their joints (Herrmann-Lunecke et al., 2022).

When looking at the street elements that were considered obstacles, two main categories arise: permanent obstacles, street elements that block or restrict pedestrian mobility on the sidewalk for an indefinite period and would require a particular intervention to remove, such as stairs or cobblestones, and temporary obstacles that block or restrict traffic on the sidewalk for a limited amount of time. Overall, more permanent obstacles were mentioned when considering all population groups, although some individuals stated that temporary obstacles, such as parked vehicles, are sometimes more troubling (Cushley et al., 2022).

Furthermore, it can be observed that some street elements are perceived as barriers, although their initial purpose was to serve as a facilitator for active mobility. Examples of this would be the ramps or kerb ramps. As mentioned by the participants in the included studies, it frequently happens that the mentioned street elements are designed improperly, too narrow, too steep or without enough landing space, and thus, they become barriers (Aldersey et al., 2018; Harris et al., 2015; Rosenberg et al., 2013). Similarly, signals at crossings, such as visual, audio and accessible pedestrian signals (APS), were also mentioned as a barrier by wheelchair users and visually impaired individuals not only when absent but also when they

were not working (Cushley et al., 2022; Harris et al., 2015; Park & Chowdhury, 2018; Wazani et al., 2021). The push button placement at crosswalks was also mentioned as a barrier, even if its existence is meant to facilitate crossing the street, as when it is placed too high or too low, it can become inaccessible for wheelchair users, for example (Park & Chowdhury, 2018; Prescott et al., 2021; Wazani et al., 2021).

2.3.3.2 Facilitators

The number of street elements perceived as facilitators for movement and accessibility is far lower than the ones perceived as barriers. Not all included studies mention facilitators, however. There is one work that focused solely on one facilitator for older adults, namely the role of benches (Ottoni et al., 2016). The authors of the study concluded that not only do benches serve as a mobility aid for older adults, allowing them to complete longer trips with some individuals even planning their route based on the locations of benches along the route, but they also facilitate social interaction, providing a sociable environment (Ottoni et al., 2016). Furthermore, Table A.2 shows that there are a considerable number of facilitators particular to visually impaired individuals. Contrary to most perceptions, one study mentioned gaps in the sidewalk as a facilitator for visually impaired individuals as they represent a source of information for orientation (Rey-Galindo et al., 2020). Beyond the street elements illustrated in Table A.2, people with visual impairments also mentioned wind direction, smells, sounds, having a mental map or asking people for directions as their own facilitators to help them orient and navigate through the environment (Rey-Galindo et al., 2020).

2.3.4 Street element frequency

The included studies highlighted different street elements as barriers or facilitators to spatial accessibility, depending on a variety of factors from the study area, the characteristics of the included participants, or the sample size of the study. However, many street elements keep reoccurring throughout the studies, suggesting they might have a higher impact. Based on how many times they were mentioned, the most frequently mentioned barriers, irrespective of the target group that mentioned them, were the width and the unevenness of the sidewalk. As for facilitators, some of the most mentioned ones were the presence of benches, wide and good sidewalk conditions and ramps designed properly. In order to try to understand if individuals perceive various street elements to have different degrees of difficulty or facilitation, heatmap tables were created based on the frequency with which the elements were mentioned in the included works (Table 2.3 and Table 2.4).

Table 2.3: Sidewalk characteristics categorised by how frequently they were mentioned as barriers in the included studies by population group considered. (MWC – manual wheelchair user; PWC – powered wheelchair user; S – scooter user; WAD – walking assistive devices user, including walker, rollator, walking stick and crutches; OA – older adults; VI – visually impaired individuals; SMR – individuals with situational mobility restriction; No. – the number of studies that mention the respective element, irrespective of its relation to a particular population group).

Barrier	MWC	PWC	S	WAD	OA	VI	SMR	No.
Sidewalk								
Width	4	6	3	1	4	2	1	11
Incline	2	4	2	1	1	1	1	7
Cross-slope	2	1	1	1		1		2
Steps/Stairs	2	4	2	1	1	1	1	6
Ramps improperly designed	3	2	2	1				3
Drain grates	1	1	1					1
Tactile paving	1	1		1				1
Undulating footpath	2	2	1	2		1		1
Poor street lighting	1	1	1	1	1	3		4
Pavement congestion		1			1	2		4
Sidewalk smoothness								
a. Uneven sidewalk	7	6	3	2	3	6	1	13
b. Lack of maintenance						1		1
c. Grass, soiling, debris	1	1	1	1	1	1		3
Sidewalk material								
a. Rough pavers with large uneven joints	2	1	1	1				2
b. Unpaved	2	2	2	1				2
c. Hard surfaces					1			1
d. Soft surfaces					1			1
Permanent Obstacles								
a. Headroom						2		2
b. Vegetation	2	3	1	2	1	2	1	6
c. Street infrastructure / furniture	2	2	1	1	2	4		6
d. Architectural						1		1
e. Street vendors					1	1		2
Temporary Obstacles								
f. Parked vehicles	2	2	1	1	3	3		6
g. Litter	1	1			1	1		1
h. Construction	1	1		1	1	2		3
Pedestrian Crosswalks								
High kerbs	4	4	2	1	2	2		7
Inappropriate kerb ramps	5	3	2	2	1	2		7
Lowered sidewalk curb						1		1

Continued on next page

Table 2.3 continued from previous page

Barrier	MWC	PWC	S	WAD	OA	VI	SMR	No.
Difficult features of crosswalks								
a. Short crossing time	2	2	1	1	1			2
b. Poor marking	3	2	1	1	1			2
c. High speed traffic	2	2	1	1	1			2
d. Too long	1							1
e. Intersection corners with multiple directions						1		1
f. Crossing side roads	1	1		1				1
Push button placement at crosswalks (too high/low)	3	3	1	1				3
Signals at crosswalks								
a. No audio signal						3		3
b. No visual signal	2	1						1
c. No accessible pedestrian signals (APS)						1		1
No high contrast between sidewalk and street						2		2
Overpass		1					1	1
Pedestrian areas / Open spaces								
Squares / open pedestrian spaces						2		2
Extreme sensory background						1		1
Shared spaces between pedestrians and other travel modes	1	1	1	1	4	1		7
Lack of...								
Lack of sidewalk	4	2	2	1		1		5
Lack of shelter and covered areas	2	2	1	1	1	1		2
Lack of places to rest	2	2	1	1	4	1		5
Lack of paving block and tactile warning						1		1
Lack of pedestrian crosswalks	3	3	1	2	2	2		4

Although the same street element was mentioned by multiple population groups, the frequency of mentioning varies significantly depending on the mobility capacities of individuals. For example, all included target groups mentioned the (narrow) width of the sidewalk as a barrier, however, out of the 11 studies this element was mentioned in, 6 were in relation to powered wheelchair users. Another example can be the frequency with which inappropriate kerb ramps were mentioned as a barrier for manual wheelchair users, with 5 out of 7 included works mentioning it. While these elements still represent barriers for other individuals as well, based on these results, it can be hypothesised that, given the heterogeneities of individual mobility capacities, different street elements could have a more significant impact on some individuals compared to others. In the case of facilitators, the majority were mentioned only once, which could be a direct consequence of studies focusing more on what elements hinder movement and accessibility. However, one interesting result is that some facilitators mirror the barriers mentioned and are also most significant for the same population groups. For example, the barrier lack of places to rest is most mentioned in the studies by older adults, and the facilitator benches are again most mentioned by older adults. Thus, the results

suggest a close relationship between barriers and facilitators, hence further stressing the importance of certain elements for some population groups.

2.4 Discussion

2.4.1 Participants and their characteristics

Due to the variation of individual needs and preferences, persons with different mobility restrictions exhibit, the diversity and size of the study sample can have a direct impact on the results of the study. The recommendations and conclusions derived from accessibility studies that exclusively focus on a single target population should be considered cautiously. Given the twofold effect of street elements formerly mentioned, the results of studies focusing on a particular population group are not immediately transferable to all individuals with mobility restrictions. Thus, this might lead to inadequate recommendations for individuals with differing disabilities (Vale et al., 2017). Improving accessibility for one population group might impact it negatively for another one if not considered simultaneously. Furthermore, the sample size used to conduct accessibility studies should also be carefully selected, as a smaller sample size may result in a lower diversity and, thus, fewer street elements reported. For example, the study of Wazani et al. (2021) included 321 participants and reported significantly more street elements than the study of Prescott et al. (2021), which included 14 participants. However, the diversity of results is influenced not only by the sample size but also by the data collection method used. For instance, the study of Rosenberg et al. (2013) included only 35 participants, but used in-depth interviews to extract a comprehensive list of barriers and facilitators for a range of mobility-restricted individuals.

Individuals with similar characteristics regarding age or walking impairment are highly heterogeneous (Wennberg et al., 2009). There is a plethora of factors that can make mobility restrictions highly variable and context-dependent, such as age, severity level, or assistive device used, creating a large spectrum of capacities even within a specific population group. For example, within the group of wheelchair users, the capacity to move through space can vary with age (i.e., an older adult with a wheelchair could experience fatigue faster) or with the type of device used (i.e., manual wheelchair, powered wheelchair, or a hybrid between the two). Although most of the included studies acknowledged between-group heterogeneities across different population groups, future research should also consider more thoroughly the within-group heterogeneities of individuals. While studies tended to differentiate which barriers or facilitators apply to which mobility-impaired individual based on the mobility device used, there was no differentiation for the groups of visually impaired individuals or older adults. Older adults also exhibit a wide spread of mobility capacities, ranging from highly mobile individuals without restrictions to those with declining capacities and finally those who experience more severe mobility restrictions and hence fall into the categories of mobility-impaired individuals. However, the majority of included studies that focused on the perception of older adults have yet to make a within-group differentiation or classification regarding their mobility capacities and perceptions of the environment. Through their study, which investigated significant barriers for wheelchair users, Harris et al. (2015) found a significant difference in how young and old wheelchair users perceive the environment, with older adults mentioning more barriers, some of which were not significant for younger

Table 2.4: Street elements categorised by how frequently they were mentioned as a facilitator in the included studies by population group considered. (MWC – manual wheelchair user; PWC – powered wheelchair user; S – scooter user; WAD – walking assistive devices user, including walker, rollator, walking stick and crutches; OA – older adults; VI – visually impaired individuals; SMR – individuals with situational mobility restriction; No. – the number of studies that mention the respective element, irrespective of its relation to a particular population group).

Facilitator	**MWC**	**PWC**	**S**	**MAD**	**OA**	**VI**	**SMR**	**No.**
Sidewalk								
Presence of sidewalk	1	1	1	1				1
Wide sidewalks	1	1	1	1	3			3
Good sidewalk conditions	3	1	1	1	1			3
Gaps in the sidewalk						1		1
Flat sidewalk or gentle slope	1	1	1	1		1		2
Separation between traffic and pedestrian areas		1			3	1	1	3
Hedged sidewalk					3			2
Clean sidewalk					1			1
No parked cars					1			1
Benches	1	1	1	1	4			5
Covered / sheltered areas	1	1	1	1				1
Adequate lighting	1	1	1	1				1
Ramps (designed accordingly)	3	3	1	1			1	3
Crosswalk								
Lowered kerb ramps	1	3	1	1		1	1	3
Kerbs					1			1
Lots of crosswalks	1	1	1	1				1
Clearly marked crosswalks	1	1	1	1		1		2
Shared pathways with minimal road crossings				1		1		1
Underpasses					1			1
Accessible pedestrian signal (APS)						3		2
Other environmental cues								
Textured landmarks						1		1
Handrails with braille for stairs						1		1
Echoes from buildings and other objects						1		1
Landmark sounds						1		1
Braille blocks						1		1
Tactile and auditory information on signs and kiosks						1		1

participants. This finding suggests the need for further examination of greater within-group variability among individuals who experience mobility restrictions.

Along the same lines, further categorisation for individuals experiencing visual impairment was not possible due to the need for more details regarding individual capacities in the included articles. Although some articles specify the different levels of visual impairment their participants exhibit, results are reported for the whole group. One article specifically addressed visually impaired individuals who utilise scooters as mobility assistive devices (McMullan & Butler, 2019). However, because it was the only study and the barriers mentioned aligned more with the ones mentioned by visually impaired individuals than the ones mentioned by scooter users, they were grouped into the same category in this article.

2.4.2 Data collection methods

Summarising the included works, it becomes apparent that studies either conducted their data collection on-site (e.g., in the urban area), off-site (e.g., at the participants' home), or a combination of both. As individuals' perceptions are inherently subjective, a potential misalignment might exist between what they say and how they act when facing the built environment. Thus, collecting data in situ allows for capturing participants' perspectives in real-time (Prescott et al., 2021), gaining a more detailed picture of the interactions between the individual, the street elements, and the strategies they employ to move through the environment (Ottoni et al., 2016). Existing literature has also demonstrated that participants engaged in walking or go-along interviews have a higher tendency to discuss the environmental features surrounding them and their use than those engaged in sit-down interviews, where the focus of the narratives shifts towards people (Evans & Jones, 2011). Further, it can make it easier for individuals to express their challenges as they are not relying only on recollection but are rather stimulated by the surrounding environment (King & Woodroffe, 2017). On the other hand, particularly when collecting data on the barriers individuals with mobility restrictions encounter in the environment, on-site data collection could restrict the number of people participating, as it might require more effort and cause frustration to encounter and overcome different challenges during the study. As street elements can make certain streets and areas inaccessible to certain individuals, on-site data collection may limit the discussion to the present street elements, leaving areas unexplored and offering an incomplete overview.

Thus, off-site data collection methodologies such as sit-down interviews might be preferred in certain cases. Examples of studies that combined the two approaches in order to maximise the amount of data collected and number of participants are studies such as Rosenberg et al. (2013) or Campisi et al. (2021), where they conducted sit-down interviews with all participants and offered them the choice to participate in a walk-along interview if they were interested and not at risk. Trying to counter the challenges imposed by on-site data collection, a growing body of literature started using images and web-based tools to overcome some of these challenges (Gao & Nagai, 2021; Saha et al., 2019; Van Cauwenberg et al., 2014). This way, participants with mobility restrictions are not at risk and can identify problems even in inaccessible areas. Among the included works, two studies used similar techniques, namely manipulated images, to study the perception of the built environment by individuals (Gao & Nagai, 2021; Van Cauwenberg et al., 2014). Other examples from the literature are studies using street view imagery to collect accessibility data (Saha et al., 2019). These approaches

make data collection more manageable, accessible, faster and scalable. Nonetheless, collecting data on-site can produce high-quality data, integrating local knowledge. Hence, the two approaches should be used complementarily.

Beyond interviews and field studies, included works also used questionnaires and focus groups to collect data from their participants. The studies that used questionnaires tended to include more participants and a wider variety of population groups (Harris et al., 2015; Wazani et al., 2021). This allowed researchers to get a better overview of the issues and challenges individuals encounter in urban environments. Using web-based questionnaires is a cost-effective methodology to collect large amounts of data in a relatively short timeframe and with few resources. Yet, the responses to a questionnaire are of limited depth, compared to other methods such as focus groups and interviews. The latter methods offer a more controlled setting, where researchers can obtain rich data and ask follow-up questions. Compared to the use of interviews, focus groups allow for the inclusion of more participants in a shorter timeframe. However, if interested in the individual needs and challenges, attention should be given to the way data are collected and documented. If not audio recorded and transcribed, the data generated from focus groups can be challenging to analyse, being hard to distinguish an individual opinion from the group opinion. Furthermore, it can also happen that individuals participating in the same group influence each other's opinions. Thus, in the context of accessibility research, focus groups can highlight between-group heterogeneities, but for individual perceptions, coupling with other methods should be considered.

2.4.3 Street elements and their frequency

The results of this review suggest that there is no one-size-fits-all solution to enable spatial accessibility. Building an urban environment serving all individuals equally is complex and challenging. From Tables 2.3 and 2.4, it became apparent that most barriers that apply to one population group will apply to others as well. Still, the different characteristics of particular street elements can facilitate mobility for some individuals and hinder it for others. Table 2.5 summarises such twofold effects.

The twofold effect of street elements can be observed not only between population groups but also within groups, supporting the aforementioned idea that individuals with similar characteristics are highly heterogeneous (Wennberg et al., 2009). Examples of this variety can be seen when looking at the perception of hard or soft sidewalk surfaces by older adults and of high kerbs or gaps in the sidewalk by visually impaired individuals. The highest contrast in how the environment is perceived is between the mobility-impaired and the visually impaired individuals. These results accentuate how different mobility capacities have different needs: Even if the magnitude of this twofold effect is context-dependent and could be minimal in certain situations, it should still not be ignored. Reasons for this twofold effect for individuals from the same population group could stem from different levels of mobility capacity. As shown in Table 2.5, different studies, including older adults, reported hard sidewalk surfaces as either a facilitator or a barrier. This difference could stem from the older adults included having different levels of mobility capacities. However, none of the corresponding studies report the level of impairment of the participant exactly, they just state that the participants are walking regularly without assistance, not giving further information about their physical health (Chen et al., 2015; Herrmann-Lunecke et al., 2022).

Nonetheless, the results indicate that the same street elements impact the spatial accessibility of individuals differently depending on the target group and individuals' mobility capacities.

Table 2.5: Street elements with a twofold effect for the spatial accessibility of different population groups. (MWC – manual wheelchair user; PWC – powered wheelchair user; S – scooter user; WAD – walking assistive devices user, including walker, rollator, walking stick and crutches; OA – older adults; VI – visually impaired individuals; SMR – individuals with situational mobility restriction)

Street element	**Barrier for:**	**Facilitator for:**
High kerbs	MWC, PWC, S, WAD, OA, VI	VI
Gaps in the sidewalk	MWC, PWC, S, WAD, OA, VI, SMR	VI
Hard sidewalk surfaces	OA	OA
Soft sidewalk surfaces	OA	OA
Tactile paving	MWC, PWC, WAD	VI

Due to the great variety of mobility capacities among individuals, it seems that there will hardly be any urban design solution that will fully satisfy all individuals and, thus, a universal design. That is, designing environments in a way that all individuals can use them without needing adaptation or specialised design (Story, 1998), seems hard to attain. Hence, some trade-offs and compromises have to be made. In the example of the high kerbs that are perceived as barriers for wheelchair users but facilitators for visually impaired individuals, one option could be to provide another type of separation between sidewalk and road accessible for both groups. One could use tactile paving to signal the end of a sidewalk, making sure that the paving is smooth enough for wheelchair users but still detectable with a walking stick. Although tactile paving has been stated as a barrier for wheelchair users, Table 2.3 shows that it has been stated only once, while high kerbs have been stated four times by manual wheelchair users and powered wheelchair users individually, making it a more significant barrier based on the frequency of mentions. Hence, the results suggest that a potential balance could be found. However, subsequent research should delve deeper into what this balance might look like.

Information such as the frequency with which certain elements are encountered in the environment or the impact they have on one's active mobility might be beneficial for design recommendations and making decisions that will enhance the spatial accessibility of the urban environment and sidewalk infrastructure. Table 2.3 and Table 2.4 show that when mentioning street elements that impact one's movement and spatial accessibility, some elements are mentioned more frequently depending on individual mobility capacity. Indeed, encountering a barrier more frequently does not imply that that specific barrier poses a higher degree of difficulty. However, when encountering several minor barriers consecutively, the effort required to overcome them can significantly increase for people who experience mobility restrictions (Wennberg et al., 2009). The study of Orellana et al. (2020) that looked at both the percentage of occurrence and the percentage of the impact of barriers for wheelchair users found that even if the order of barriers for the two lists was not the same, some of the most occurring barriers were also some of the most impactful ones. Thus, looking at the frequency with which street elements were mentioned in the included studies indicates

how these elements are perceived differently by population groups. For example, the lack of places to rest was mentioned by all population groups except individuals with situational mobility restrictions. However, it was mostly mentioned by older adults, highlighting that this barrier is more significant for this population group. Moreover, this was also confirmed by the study of Ottoni et al. (2016), which looked at the different roles benches have for the experience of mobility and well-being of older adults.

Mentions of street elements that facilitate movement through space were relatively infrequent, which is understandable given the fact that most articles were primarily focused on investigating the presence of barriers that hinder movement through the environment for individuals. Looking at Table A.2, the results indicate that most facilitators mentioned are, in fact, the opposite of the mentioned barriers (e.g., narrow vs. wide sidewalk; uneven vs. paved, smooth sidewalk). Hence, this suggests that tackling and eliminating the mentioned barriers could be enough to facilitate movement in some instances. However, this is not the case with all facilitators, where particular actions beyond simple removal of barriers should be taken, such as adding places to rest and tactile paving.

Practical relevance: The results of this systematic review, as well as the recommendations made below in the Conclusion, can be used as a basis for urban planners and policymakers to understand, assess and initiate action, to create a more inclusive environment for different population groups. Although most countries have developed their own accessibility regulations and guidelines, empirical studies, as the ones summarised in this review, have established that at times these regulatory documents do not incorporate the entire needs of mobility-restricted individuals (Orellana et al., 2020). Furthermore, studies have also found that certain barriers which hinder active mobility are sometimes not considered in accessibility policies (Wennberg et al., 2009). Thus, this systematic review can help address these gaps and provide a consolidated basis to complete or amend existing accessibility guidelines and regulations. Furthermore, the information extracted from the heatmap tables (Tables 2.3 and 2.4) is relevant not only to differentiate the impact of the built environment on individual spatial accessibility but could also aid urban planners to prioritise interventions based on what barriers have a higher frequency.

2.4.4 Limitations

Although this review includes studies focusing on four different population groups, the main limitation is its lack of a more comprehensive classification for older adults, visually impaired and situational mobility-restricted individuals. As it is the case for mobility-impaired individuals, where the impact of street elements can differ based on the mobility assistive device used, also older adults can have varying mobility capacities and based on these could perceive the environment differently. Likewise, there exists a spectrum of impairments for visually impaired individuals (e.g., mild or moderate vision loss) as well as a variety of assistive devices that could influence the movement through the environment of an individual and bring new perspectives on what street elements would prove to be barriers or facilitators. However, none of the included studies considered these within-group heterogeneities, and thus, they could not be represented in the results of this study.

Another limitation of this study is that only a limited number of included studies present their perspectives for some particular population groups. This is the case with individuals using rollators, walkers, crutches, and walking sticks, as well as individuals with situational mobility restrictions, each of which was covered by only two articles. Thus, the results of this study may not represent a significant part of the perceptions of these population groups. Furthermore, there is no difference in perceptions considered between the users of different mobility aid devices, although it could be that for a rollator user, an uneven sidewalk could represent a significant barrier (as it is the case for wheelchair or scooter users) but not for individuals with a walking stick. Nonetheless, the results of this study can be used to understand the interaction between the built environment and mobility-impaired individuals using different mobility assistive devices.

Finally, the search query, combined with the eligibility criteria used, resulted in 20 studies included in the final review. In this review, only the street elements mentioned by participants in the selected studies are considered. Thus, other studies might reveal more street elements, and the results and significance of the ones presented in this study might change. However, this review includes studies from around the world, and the number of studies covering each population group separately is sufficient to assume that at least the street elements that significantly impact spatial accessibility were mentioned. Furthermore, this study did not actively include public transportation when searching for articles, for reasons explained in Section 2.2.3. Thus, it is possible that the search missed out on articles that focus on the elements that impede or facilitate movement for different individuals within the public transportation context. However, the search query was broad enough to be able to catch these types of articles if they were also focusing on microscale street elements. Moreover, two of the included articles have a focus on public transportation (Klicnik & Dogra, 2019; Park & Chowdhury, 2018), but were included because they also have a significant focus on microscale street elements.

2.5 Conclusion

The aim of this systematic literature review was to understand how individuals with various mobility restrictions perceive different microscale street elements that impact their movement through the city. Over a ten-year period, we identified 20 studies and extracted information regarding the population groups included, the data collection methods used, and the street elements mentioned in each study. The analysis of the included works according to the four research questions mentioned in Section 2.2.1 revealed the following results:

- **Participants and their characteristics.** The included works tend to focus on a single population group and consider within-group differences only with respect to mobility-impaired individuals and the different mobility assistive devices used within that group. The sample size used for such accessibility studies varied greatly, influencing the diversity of perspectives that were included.
- **Data collection methods.** Generally, qualitative research methods are used to extract the individuals' perceptions of the built environment. The most frequently used data collection methods are interviews, both sit-down and walk-along, although other methods such as questionnaires, field studies and focus groups are also used. To

be able to include more participants and capture mode details, studies tend to use a mixed-methods approach, combining sit-down and walk-along interviews, or focus groups and field studies.

- **Perception of street elements.** The amount of microscale street elements mentioned to hinder or facilitate movement through space varied greatly between the included works. Numerous elements were perceived similarly across multiple population groups, however several studies showed that, given the different characteristics of an element (e.g., the height of a kerb), certain street elements can be, both, a barrier for one individual and a facilitator for another. In general, fewer street elements that act as a facilitator for movement were mentioned when compared to barriers. Elements that were meant to be facilitators, but are inappropriately constructed (e.g., ramps that are too steep, kerb ramps that are too narrow) or are not working (e.g. pedestrian signals at crosswalks), were also mentioned as barriers.
- **Frequency of street elements.** An analysis of the frequency with which street elements were mentioned across the studies revealed that even if the same element was identified as a barrier by multiple population groups, its impact on their individual accessibility may differ drastically. Overall, the included studies show that when considering the diversity of mobility capacities that individuals have, focusing on between- and within-population group heterogeneities, street elements can have a twofold impact on spatial accessibility and designing a barrier-free space for anyone is a challenging task.

Based on the results of this review, the following recommendations can be made:

- Studies concerned with the accessibility of the built environment should focus more on the varying mobility capacities that exist within a population group, especially regarding the groups of visually impaired individuals and older adults, respectively, which so far have been treated as homogenous. The majority of included works that focus on the group of mobility-impaired individuals have shown that depending on the mobility capacity or assistive device used the individual perception of the environment changes. Thus, this should also be investigated and considered for other population groups.
- Depending on the goal, the study design used to investigate the perception of individuals of the built environment should allow for capturing detailed individual information, while making sure to include a representative sample of the respective target population group.
- Regarding the microscale street elements, future studies should not only highlight whether a street element hinders or facilitates movement for an individual, but also focus on the underlying reasons. Considering not only the street elements, but also their characteristics that make them barriers or facilitators for movement, is essential for assessing accessibility and finding solutions to change the environment to make it more inclusive.
- Collecting data on the perceived difficulty of the street elements or the frequency with which they are encountered in the environment can offer further insights into how and what infrastructure interventions should be prioritised.

Future research can build on this literature study and use such detailed information regarding individual perception for personalised routing or accessibility modelling, helping to parametrise models such as microsimulations or agent-based models. These methods can facilitate simulating the effects of planning interventions, such as physical barrier removal and implementation of facilitators. Furthermore, the results of this work — possibly implemented in simulation studies — can serve as a basis for civil engineers and urban planners to identify inaccessible areas, prioritise tackling physical barriers and develop new design solutions that will make the urban built environment more accessible and inclusive. There is an urgent need to find solutions that satisfy the conflicting accessibility needs of different individuals by considering the high variation in mobility capacities of the population.

3

How mobility restrictions shape perceptions of pedestrian infrastructure

Chapter Outline

This chapter is adapted from the following manuscript submitted for publication:

Georgescu, A.I., Allahbakhshi, H., Darvishy, A., & Weibel, R. (submitted). Same sidewalk, different experiences: How mobility restrictions shape perceptions of urban pedestrian infrastructure and accessibility. *Travel Behaviour and Society*.

Supplementary material can be found in Appendix B.

Scope: Empirically analyse between- and within-group variation in the perceived severity and facilitation levels of microscale street elements across different mobility-restricted population groups.

Approach:

- Conducted a large-scale online survey to collect data on individuals' perceptions of microscale street elements.
- Quantified between-group differences in the perceived severity and facilitation levels of microscale street elements across four population groups.
- Examined within-group variation in perceptions based on characteristics such as age, gender, and use of mobility assistive devices.
- Integrated perception data into spatial accessibility analyses to demonstrate its impact on accessibility outcomes.

Key insights:

- Perceptions of microscale street elements differ systematically between population groups, with the largest differences observed between mobility-impaired and visually impaired individuals.
- Differences between groups are more pronounced for barriers than for facilitators.
- Within-group variation in perceptions is generally less pronounced and less consistent, with mobility capacities playing a more dominant role than age or gender.
- Incorporating perception-based data into routing analyses leads to noticeably different outcomes.

Contribution of the PhD candidate: The PhD candidate designed and implemented the study, including survey development and data collection. The PhD candidate performed the statistical analyses, interpreted the results, and led the writing of the manuscript.

CRediT Authorship Roles: Alexandra-Ioana Georgescu: Conceptualisation, Methodology, Software, Formal analysis, Investigation, Data Curation, Writing – original draft, Writing – review & editing, Visualisation. Hoda Allahbakhshi: Conceptualisation, Methodology, Resources, Writing – review & editing, Supervision, Funding acquisition. Alireza Darvishy: Resources, Writing – review & editing. Robert Weibel: Conceptualisation, Methodology, Resources, Writing – review & editing, Supervision, Funding acquisition.

3.1 Introduction

Individual spatial accessibility in urban environments is shaped by a wide range of factors, including transport infrastructure, the distribution of public facilities, the attractiveness and perceived safety of spaces, wider socio-economic conditions, and personal capabilities. As urbanisation accelerates (United Nations, 2019) and the prevalence of disability rises (World Health Organization, 2022), understanding how internal factors (i.e. individual mobility capacities) and external factors (i.e. physical barriers or facilitators) influence movement through urban areas becomes increasingly critical. Such understanding is essential to ensuring accessible and walkable urban spaces, conditions that underpin social sustainability, foster inclusion, promote public health, and enhance urban residents' quality of life.

For individuals with mobility restrictions or disabilities, everyday pedestrian mobility is often shaped by microscale street elements such as high kerbs, stairs, sidewalk obstacles, or ramps. While spatial accessibility – the ease of reaching desired destinations (Hansen, 1959) – is often associated with the shortest or fastest routes for the general population, individuals with mobility restrictions frequently prioritise barrier-free routes (Gharebaghi et al., 2021). Features such as high kerbs or construction sites can therefore substantially reduce, or even prevent, accessibility for certain users (Vale et al., 2017), with consequences for physical and mental health, social participation, and overall well-being (Lid & Solvang, 2016; Rantakokko et al., 2014). Incorporating the perceptions of individuals with diverse mobility restrictions regarding microscale street elements in urban areas when evaluating spatial accessibility is thus necessary to prevent overestimating accessibility.

However, microscale street elements are not experienced uniformly across individuals with different mobility restrictions. Wheelchair users, for example, may perceive high kerbs as significant barriers (Harris et al., 2015), whereas individuals with visual impairments may regard them as useful tactile boundaries separating the sidewalk from the road (Han et al., 2020). Even when widely recognised as barriers, the degree to which elements obstruct mobility varies: stairs constitute an impassable barrier for wheelchair users but may remain passable, though with difficulty, for older adults or individuals with visual impairments. Moreover, heterogeneity exists not only between groups but also within them, shaped by characteristics such as age, gender, familiarity with the environment, physical fitness, and the type of mobility-assistive device used (Harris et al., 2015; Prescott et al., 2021). Despite this variability, few studies systematically compare how individuals with differing mobility capacities perceive microscale street elements.

Focusing on four population groups with different types of mobility restrictions, including 1) mobility-impaired individuals, 2) visually impaired individuals, 3) situationally restricted individuals (e.g., caregivers or parents with pushchairs), and 4) older adults aged 65 and above with mobility restrictions, this study addresses this gap and aims to identify which specific microscale street elements are perceived differently across groups and to what extent heterogeneity exists both between and within these groups. This study aims to achieve the following research objectives:

RO1. Between-group variation: Examine how population groups with different mobility capacities perceive the impact of various microscale street elements on their movement through urban environments.
RO2. Within-group variation: Assess the extent of within-group variation in perceptions of microscale street elements.
RO3. Perceptual influences on movement and accessibility: Analyse how differences in perceptions of microscale street elements influence individuals' movement patterns and accessibility within urban spaces.

3.2 Related work

Accessibility is a multidimensional concept encompassing the spatial distribution of opportunities, transport system characteristics (e.g., travel time or cost), temporal constraints (e.g., opening hours), and individual factors such as preferences or mobility capacities (Geurs & Van Eck, 2001). Within this framework, a distinction is commonly made between objective (or calculated) accessibility, referring to measurable indicators such as distance, time, or cost, and perceived accessibility, which reflects individuals' subjective evaluations of their ability to navigate the built environment (Geurs & Van Wee, 2004; Lättman et al., 2018). As such, perceived accessibility complements objective measures and provides insight into how accessibility is experienced across contexts and transport modes (Lättman et al., 2016).

Differences in perceived accessibility are particularly important for pedestrian mobility in urban environments. In this study, microscale street elements are defined as small-scale features of sidewalks, crossings, and pedestrian areas, such as sidewalk width, kerb ramps, or stairs, that individuals encounter during their trips, and that may impede or facilitate movement for people with mobility restrictions (Lid & Solvang, 2016). Existing studies show that such elements, including sidewalk quality and physical barriers, often influence walking accessibility more strongly than connectivity, attractiveness, or land-use diversity for individuals such as older adults or wheelchair users (Jehle et al., 2024). However, many studies aggregate microscale street elements into composite attributes, such as "freedom from barriers" or "accessible pedestrian network" (Gaglione et al., 2022; Jehle et al., 2024; Moura et al., 2017), limiting understanding of which specific elements most strongly affect movement.

Only a small number of studies examine which microscale street elements influence the movement of individuals with mobility restrictions (Jenkins et al., 2015; Klicnik & Dogra, 2019; Neven & Ectors, 2023; Rosenberg et al., 2013; Wazani et al., 2021). Most rely on qualitative methods such as questionnaires (Wazani et al., 2021), interviews (Rosenberg et al., 2013), or focus groups (Neven & Ectors, 2023) to identify barriers and facilitators across population groups. While these approaches identify relevant elements, they rarely capture the extent to which barriers impede movement, often treating them as either obstructing or non-obstructing, despite their often nuanced effects, such as reducing walking speed or requiring detours.

To address limitations associated with binary representations of microscale street elements, some studies have introduced ranked-response scales to capture perceived importance or difficulty of these elements (Baris & Uslu, 2009; Harris et al., 2015; Wennberg et al., 2009). Wennberg et al. (2009) used questionnaire-based methods to examine how older adults perceived the importance of microscale street elements, comparing younger-old and older-old groups using a five-point Likert scale ranging from very unimportant to very important. Baris and Uslu (2009) similarly showed that individuals with different impairments perceive microscale street elements differently. However, their approach relied on participants' ratings of their agreement with predefined statements, which limited the comparability of the relative importance of specific elements across groups. Building on this perspective, Harris et al. (2015) used a web-based survey to assess perceived difficulty associated with 50 barriers encountered by wheelchair users, with participants rating each element on a four-point Likert scale ranging from "not difficult" to "prevents me from going out". Despite capturing variation in perceived difficulty, results were reported primarily in terms of whether participants could or could not navigate each element, limiting insight into how perceived difficulty varied across specific elements and user characteristics.

More recent studies have begun to examine individual perceptions of microscale street elements and differences in these perceptions between and within population groups (Bredmose et al., 2023; Li et al., 2025). For example, Bredmose et al. (2023) developed a questionnaire to quantify, using a five-point Likert scale, the perceived importance of microscale street elements across four levels of visual impairment, revealing substantial variation in how elements such as tactile paving, visual delineation of walkways, and cues indicating lowered kerbs were valued. Similarly, Li et al. (2025) conducted an image-based survey in which users of different mobility aids assessed the passability of microscale street elements based on their personal experiences, identifying numerous between-group differences in perceived difficulty. Taking this approach a step further, Li et al. (2025) incorporated their survey results into a personalised routing tool, demonstrating how differences in perceived passability can influence route choice. Nevertheless, despite extending previous work, especially compared with earlier studies that relied on literature-based rather than empirically derived weights in accessibility analyses (Jehle et al., 2024), the set of microscale street elements examined and the population groups included remained limited.

Despite growing recognition of the role of microscale street elements in shaping pedestrian accessibility, several key gaps remain. First, existing research rarely captures how the perceived impact of specific elements varies across different population groups, as studies focusing on subjective experiences typically examine only a single group, limiting the ability to draw robust cross-group comparisons. Second, where multiple groups are included, analyses are often descriptive, emphasising the presence of barriers or facilitators rather than differences in their perceived severity or impact. Finally, there is limited empirical evidence systematically linking these perceptual differences to their implications for mobility in urban environments. Addressing these gaps is essential for developing accessibility assessments that more accurately reflect the diverse ways in which microscale street elements enable or constrain movement.

In this article, we report on a comprehensive online survey we conducted to determine how perceptions of microscale street elements vary across mobility capacities. We included

four population groups representing a broad spectrum of mobility restrictions and assessed perceptions of 28 microscale street elements, covering both barriers and facilitators, using a five-point Likert scale to capture degrees of perceived permeability. We further analysed both between-group and within-group variation associated with individual characteristics, such as age, gender, and assistive device use, and integrated the results into a routing and accessibility analysis framework to demonstrate how differing perceptions translate into distinct most-accessible routes for different individuals.

By incorporating perception-informed evidence into accessibility modelling, this study contributes to the development of more inclusive, user-centred representations of pedestrian networks that better reflect how diverse populations experience urban environments. Such advances enable the design of personalised navigation and decision-support systems tailored to differing mobility needs. From a planning perspective, these improved modelling approaches can support the prioritisation of accessibility interventions, inform inclusive mobility strategies, and guide the design of urban environments that promote equitable mobility opportunities for all individuals.

3.3 Materials and methods

3.3.1 Participant recruitment and questionnaire administration

Individuals were eligible to complete the questionnaire if they were over 18 years old, residents of an urban area in Switzerland, as defined by the Federal Office of Statistics (Federal Office of Statistics, 2020), and had some form of mobility restriction when walking through the urban environment, including: individuals with mobility impairments, visual impairments, individuals with situational restrictions (such as parents with pushchairs, caregivers, individuals who suffered an accident), and mobility-restricted individuals aged 65 and above. Due to difficulties in identifying eligible participants and encouraging participation among individuals aged 65 and above with mobility restrictions, one inclusion criterion was slightly relaxed to include not only individuals residing in urban areas but also those with experience of, and frequent movement through, urban environments.

Recruiting participants from the target populations required multiple strategies. A purposive sampling approach was adopted, beginning with contacting associations, foundations, and health centres that support individuals with mobility restrictions, while snowball sampling further extended participation through community networks. Because recruiting mobility-impaired and mobility-restricted individuals aged 65 and above proved challenging, additional participants were recruited with external support (Enable Me, 2026). Participation was also encouraged through the authors' professional and personal networks, website announcements, and printed flyers. Each population group had a target of 30 responses to ensure balanced comparisons. As the groups required tailored approaches, data collection was conducted sequentially: first, individuals with mobility impairments, followed by those with visual impairments, individuals with situational mobility restrictions, and finally, older adults.

The questionnaire was primarily administered online via LimeSurvey (version 6.15.5) (LimeSurvey, 2025), initially developed in English and translated into German, the local language of the participants. To enhance accessibility, participants could also complete it over the

phone or on paper at their location. Informed consent was obtained prior to participation, and all data were anonymised for analysis. Participants received a 20 CHF grocery voucher as compensation for their time. Prior to data collection, the study protocol was evaluated using the university's ethics self-assessment tool. The assessment determined that formal ethical approval was not required.

3.3.2 Questionnaire design and development

The questionnaire (Appendix B, Section B.1) consisted of 26 closed-ended and two open-ended questions, organised into four sections: participant characteristics, perceptions of barriers, perceptions of facilitators, and overall perceptions of the built environment:

- The first section collected information on participants' personal characteristics, including the target group they most identified with, age, gender, postal code, income, education level, use of mobility-assistive devices, and pedestrian profiles, such as walking frequency and purpose.
- The second and third sections each contained three questions, where participants were asked to: (1) select elements they perceived as barriers or facilitators from a predefined list, (2) rate the severity or facilitation level of each element using a 5-point Likert scale (barriers: 1 = fully passable to 5 = not passable; facilitators: 1 = very facilitating to 5 = not facilitating), and (3) indicate how frequently they encountered each element in their daily mobility using a 5-point Likert scale (1 = always to 5 = never). The lists of potential barriers (n=19) and facilitators (n=9) were developed based on Swiss official accessibility guidelines and a comprehensive literature review (Authors, 2024). To reduce interpretation errors, each element was accompanied by illustrative images. A comprehensive list of the elements, along with detailed explanations, is provided in Appendix B.1, Table B.1.
- The final section contained questions regarding the participants' perceptions of their own neighbourhood's accessibility and the main factors limiting their walking or wheeling in daily life.

The questionnaire was developed through an iterative process and piloted with 10 participants, both experts and individuals from the target population groups, to test its validity and reliability. Based on their feedback, two questions were removed due to redundancy or excessive complexity, and several others were reworded for clarity. Pilot responses were included in the main dataset if participants met the inclusion criteria and their data were complete, resulting in eight of the ten pilot responses being retained. The final questionnaire required approximately 20–30 minutes to complete.

3.3.3 Statistical analysis

3.3.3.1 Between-groups variation

To assess whether perceptions of microscale street elements differed across the four population groups, nonparametric statistical tests were employed owing to the ordinal (Likert-type) and non-normally distributed nature of the data, and the relatively small group sizes. The Kruskal–Wallis test (Kruskal & Wallis, 1952) was first used to identify microscale street elements exhibiting significant between-group differences in perceived severity or facilitation.

Where significant overall effects were detected, pairwise comparisons were conducted using Dunn's post hoc test (Dunn, 1964) to identify the specific groups in which these differences occurred.

3.3.3.2 Within-groups variation

Exploratory within-group analyses were conducted to examine whether perceptions of microscale street elements varied according to selected individual characteristics. The characteristics considered were mobility-assistive device use, age, and gender. The influence of mobility-assistive device type on perceived barrier severity and facilitator helpfulness was examined only within the mobility-impaired group, as nearly all participants in this group reported using an assistive device, and sufficient observations were available for statistical testing. Age and gender were examined within all four population groups.

Differences in perceptions associated with mobility-assistive device type and gender were assessed using the Mann–Whitney U test (Mann & Whitney, 1947) within each population group, as a non-parametric method suitable for comparing two independent groups with ordinal data. Associations between participants' age and their ratings of barrier severity or facilitator helpfulness were examined using Spearman's rank correlation coefficient (Spearman, 1904).

3.3.4 Perceptual influences on movement and accessibility

To showcase the effects of incorporating perception data into accessibility analyses, we integrated survey-derived perception data into an enriched pedestrian network and computationally modelled accessible routes tailored to individual needs. This approach illustrates how variation in the perceived impact of microscale street elements leads to differences in routing outcomes and accessibility patterns across population groups.

A pedestrian network was enriched with detailed data on microscale street elements (Allahbakhshi & Ardüser, 2024; Allahbakhshi et al., 2026), including sidewalk width, slope, surface quality, presence of physical barriers, and more (Georgescu et al., 2025). These attributes were combined with segment length and perception-based weights derived from the survey, calculated as the median rating per microscale street element and population group. Each network segment was thus assigned a composite impedance cost reflecting both physical accessibility conditions and group-specific needs. Routes were then computed between origins and destinations by minimising this cost, allowing accessibility outcomes to vary according to different perception profiles. The full methodology and spatial data used for constructing the enriched network, deriving perception weights, and implementing the routing procedure is described in detail in Georgescu et al. (2025) and Georgescu et al. (2026).

Applying the above-described framework, we calculated pedestrian routes between geolocated address points and supermarkets in District 1 (i.e., the inner city) of Zurich, Switzerland, for our four population groups. Routes were computed separately for each group using the same underlying pedestrian network but group-specific perception weights. From the resulting set of origin-destination pairs, we selected one illustrative example that exhibits substantial divergence in routing outcomes across population groups to highlight how differences in perceived accessibility can lead to markedly different route choices under otherwise identical

spatial conditions. This component of the analysis was intended primarily as a qualitative illustration rather than a systematic quantitative evaluation; additional analyses using the same approach are presented in Georgescu et al. (2026).

3.4 Results

3.4.1 Sample description

Between November 2024 and October 2025, 167 individuals completed the questionnaire. Of these, we excluded 20 due to not meeting the eligibility criteria and 27 due to incomplete, duplicated, or unreliable responses. The final sample included 120 participants for analysis. Participants were evenly distributed across the four study groups, with 30 participants per group. Detailed demographic and mobility-related characteristics of the sample are presented in Appendix B, Table B.2. Across groups, mean ages ranged from 39.9 years (mobility-impaired individuals) to 80.7 years (older adults), and women constituted the majority in all groups, ranging from 17 to 20 per group.

Mobility-assistive device use varied widely across groups. Most mobility-impaired participants reported using manual or powered wheelchairs, whereas the majority of situationally restricted participants reported no assistive device use. Visually impaired participants primarily relied on white canes or assistance dogs, while older adult participants reported a mix of walking aids or no device. Regarding mobility habits, approximately 56.7% of respondents reported walking or wheeling for transport frequently or very frequently (i.e., more than five times per week), whereas only 13.3% reported never using this mode. Leisure-related walking or wheeling occurred less frequently, with only 27.5% of respondents walking or wheeling five or more times per week. The most frequently reported reasons for walking or wheeling were access to nearby destinations (29.1%) and health or exercise benefits (20.8%). Conversely, the most reported reasons for avoiding walking or wheeling were barriers encountered on sidewalks, crossings, or pedestrian areas (30.8%), followed by a lack of nearby amenities (14.1%), unattractive environments (13.3%), and safety or security concerns (13.3%). Nearly 25% of respondents reported other reasons or indicated that they did not avoid walking or wheeling for any reason. Regarding perceived environmental constraints, 35.8% of respondents reported that the built environment was slightly limiting for their daily mobility, while 13.3% considered it very or extremely limiting. By contrast, 30.8% reported no perceived limitations.

3.4.2 Between-groups variation

3.4.2.1 Impact of barriers

Kruskal-Wallis tests indicated statistically significant differences between the four population groups in perceived barrier severity for nearly all assessed microscale street elements at the 5% significance level (Table 3.1). Only the absence of zebra crossings and the lack of places to rest indicated comparable perceptions across groups.

Further, post hoc pairwise comparisons using Dunn's test with Holm-adjusted p-values were conducted to identify specific group differences (Figure 3.1). While the lack of street lighting showed a significant overall group effect in the Kruskal–Wallis test, no significant pairwise differences remained after adjustment.

Table 3.1: Results of the Kruskal-Wallis tests for the 19 barriers included in the survey, sorted by the effect size (ϵ^2) representing the extent to which differences between groups account for the variation in severity ratings. The mean rank is equal to the average rank of the responses within a group. The maximum rank is 120. Population groups: MI = mobility-impaired, OA = older adults, SR = situationally restricted, VI = visually impaired.

Microscale street elements	**Mean Rank**				**Kruskal–Wallis**			
	MI	OA	SR	VI	H	df	p-value	$\epsilon^2
Sidewalk features								
Stairs	88.717	59.133	62.717	31.433	43.887	3	0.000***	0.369
Steep sidewalk	77.05	77.017	53.267	34.667	33.738	3	0.000***	0.284
Sidewalk material type	74.5	73.233	37	57.267	24.319	3	0.000***	0.204
Uneven sidewalk	76.933	67.5	39.833	57.733	20.48	3	0.000***	0.172
Cross-slope	72.3	71.033	55.467	43.2	15.349	3	0.002**	0.129
Shared pedestrian spaces	49.333	63.117	51.633	77.917	13.661	3	0.003**	0.115
Small-scale obstacles	71.833	55.9	44.567	69.7	13.141	3	0.004**	0.11
Large-scale obstacles	79.2	55.183	54.833	52.783	12.486	3	0.006**	0.105
Narrow sidewalk	76.9	57.65	58.3	49.15	10.992	3	0.012*	0.092
Missing sidewalk	75.3	52.017	53.267	61.417	8.979	3	0.030*	0.075
Lack of street lighting	60.833	67.3	45.783	68.083	8.222	3	0.042*	0.069
Lack of places to rest	61.45	66.717	60.75	53.083	3.371	3	0.338	0.028
Crossing features								
High kerb	90.967	63.867	48.133	39.033	41.241	3	0.000***	0.347
No accessible signals at intersection	51.983	55.6	48.8	85.617	23.404	3	0.000***	0.197
Crossing surface problems	69.967	70.233	40.233	61.567	16.338	3	0.001***	0.137
Tram tracks at crossing	72.45	57.7	43.117	68.733	14.188	3	0.003**	0.119
Faded zebra crossing markings	51.15	67.383	50.5	72.967	13.341	3	0.004**	0.112
Long crossing	63.917	65.45	42.633	70	12.015	3	0.007**	0.101
No zebra crossing	58.017	60.767	55.567	67.65	2.206	3	0.531	0.019

The presence of stairs showed the greatest variation in perceptions across groups in both tests, with a large effect size ($\epsilon^2 = 0.37$) in the Kruskal-Wallis test and significant differences between nearly all pairs in the post hoc test. Further elements that were among the most divergent-perceived elements were the presence of high kerbs ($\epsilon^2 = 0.35$), the steepness of the sidewalk ($\epsilon^2 = 0.284$) and the absence of accessible signals at intersections ($\epsilon^2 = 0.197$).

Overall, individuals with mobility impairments consistently assigned higher severity ratings to sidewalk-related barriers than other groups, as reflected in both Figure 3.1 and the mean ranks in Table 3.1. However, statistically significant differences relative to other groups were limited to specific elements, including stairs, steep sidewalks, high kerbs, and large-scale obstacles. Severity ratings from mobility-impaired participants were often closely aligned with those of mobility-restricted older adults, particularly for narrow sidewalks, surface quality, and crossing-related elements.

In contrast, visually impaired participants rated crossing-related barriers as more severe than the other groups, particularly the absence of accessible pedestrian signals, faded zebra

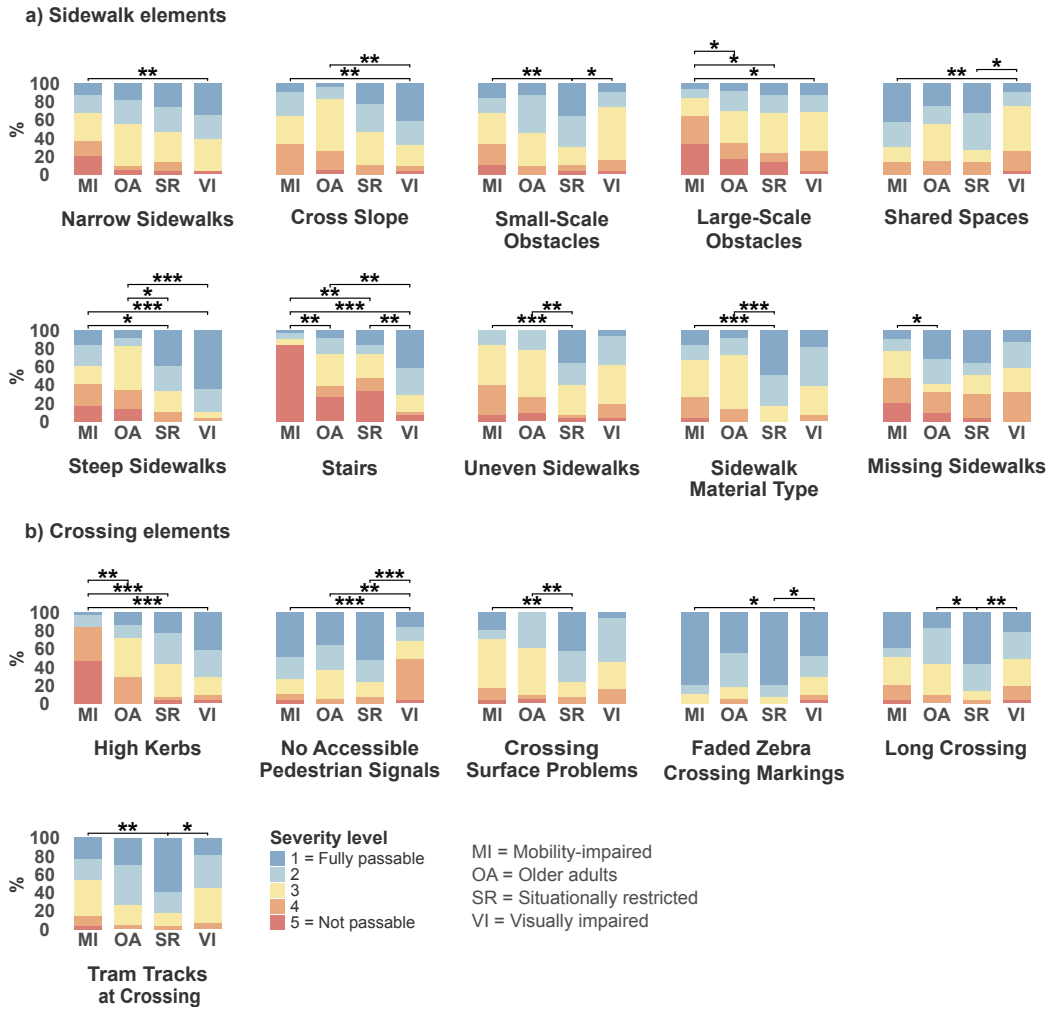


Figure 3.1: Distribution of perceived severity levels for microscale street elements showing significant pairwise differences in Dunn's post hoc tests. Panel (a) presents sidewalk elements, while panel (b) presents crossing elements. Stacked bar charts display the proportion of responses across severity levels (1 = fully passable to 5 = not passable) for each population group. Horizontal bars above each panel indicate statistically significant pairwise group differences identified by the Dunn test. Asterisks denote significance levels as follows: * = $p < 0.05$, ** = $p < 0.01$, *** = $p < 0.001$. Effect sizes and detailed Dunn test results are reported in Appendix B, Table B.3.

crossing markings, long crossing distances, and the absence of zebra crossings. Participants with situational mobility restrictions generally rated most barriers as less severe than other groups. However, they perceived stairs and narrow sidewalks as more challenging than did visually impaired participants and older adults.

Across all barriers, the largest perceptual disparities were observed between mobility-impaired participants and those with situational mobility restrictions or visual impairments, with significant differences identified for nine of the nineteen assessed elements as stated below:

- Mobility-impaired versus visually impaired individuals: narrow sidewalks; cross slope; large-scale obstacles; shared spaces; steep sidewalks; stairs; high kerbs; no accessible pedestrian signals and faded zebra crossing markings
- Mobility-impaired versus situationally restricted individuals: small- and large-scale obstacles; steep sidewalks; stairs; uneven sidewalks; sidewalk material type; high kerbs; crossing surface problems; and tram tracks at crossings

The smallest disparities were observed between mobility-impaired or visually impaired participants and mobility-restricted older adults, for whom significant differences were identified for only four elements, as follows:

- Mobility-impaired versus mobility-restricted older adults: large-scale obstacles; stairs; missing sidewalks; and high kerbs
- Visually impaired individuals versus mobility-restricted older adults: cross slope; steep sidewalks; stairs; and no accessible pedestrian signals

3.4.2.2 Impact of facilitators

Similarly to barriers, the Kruskal–Wallis tests revealed statistically significant between-group differences for most facilitators (Table 3.2). Only adequate street lighting and the presence of zebra crossings showed no significant differences across groups.

The results from Dunn's post hoc test showed, in general, fewer disparities across groups for facilitators than for barriers (Figure 3.2). The largest perceptual disparities occurred for sidewalk flatness and the presence of accessible pedestrian signals, with visually impaired participants differing significantly from all other groups. Visually impaired participants also differed significantly from mobility-impaired participants for most facilitators, including flat sidewalk; wide sidewalks; smooth sidewalks; separated space for pedestrians and other vehicles; lowered kerbs and accessible pedestrian signals at crossings; generally rating them as less facilitating, except for separated pedestrian paths and accessible pedestrian signals. Most of the participants with situational restrictions found all elements as facilitating or very facilitating, including flat sidewalks; wide sidewalks; smooth sidewalks; separated space for pedestrians and other vehicles and lowered kerbs. Same as for barriers, older adults showed rating patterns largely comparable to those of mobility-impaired participants.

Table 3.2: Results of the Kruskal-Wallis tests for the nine facilitators included in the survey, sorted by the effect size (ϵ^2), representing the extent to which differences between groups account for the variation in level of facilitation ratings. The mean rank is equal to the average rank of the responses within a group. The maximum rank is 120. Population groups: MI = mobility-impaired, OA = older adults, SR = situationally restricted, VI = visually impaired.

Microscale street element	**Mean Rank**				**Kruskal–Wallis**			
	MI	OA	SR	VI	H	df	p-value	ϵ^2
Sidewalk elements								
Flat sidewalk	53.05	53.05	55.383	81.823	18.256	3	0.000***	0.152
Separated pedestrian space	75.267	57.65	63.467	48.048	11.41	3	0.010**	0.095
Smooth sidewalk	49.8	53.267	68.167	72.387	10.913	3	0.012**	0.091
Wide sidewalk	54.133	59.3	54.083	75.984	9.729	3	0.021**	0.081
Places to rest	66.783	46.1	60.467	70.339	9.363	3	0.025**	0.078
Adequate street lighting	56.367	58.083	71.467	58.177	3.932	3	0.269	0.033
Crossing elements								
Lowered kerb	45.25	61.567	57	79.565	19.439	3	0.000***	0.162
Accessible signals at intersection	67	65.283	72.7	39.726	18.021	3	0.000***	0.15
Zebra crossing	65.15	58.783	62.183	57.984	0.93	3	0.818	0.008

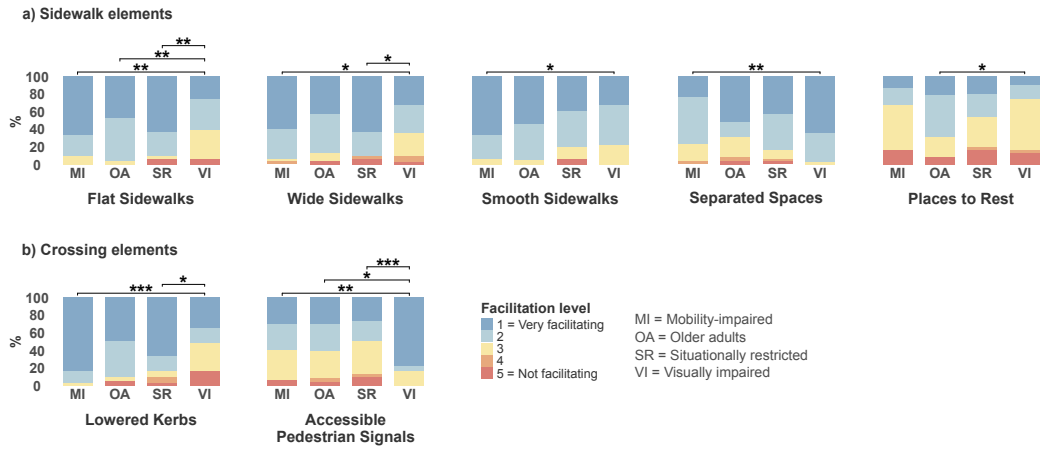


Figure 3.2: Distribution of perceived facilitation levels for microscale street elements showing significant pairwise differences in Dunn's post hoc tests. Panel (a) presents sidewalk elements, while panel (b) presents crossing elements. Stacked bar charts display the proportion of responses across severity levels (1 = very facilitating to 5 = not facilitating) for each population group. Horizontal bars above each panel indicate statistically significant pairwise group differences identified by the Dunn test. Asterisks denote significance levels as follows: * = $p < 0.05$, ** = $p < 0.01$, *** = $p < 0.001$. Effect sizes and detailed Dunn test results are reported in Appendix B, Table B.4.

3.4.3 Within-groups variation

Beyond between-group comparisons across different mobility impairments or restrictions, we conducted exploratory within-group analyses to examine additional sources of heterogeneity in individuals' perceptions of microscale street elements. Specifically, we investigated whether perceptions of microscale street elements varied within groups by mobility-assistive device use, gender, and age.

3.4.3.1 Mobility assistive device

Within the mobility-impaired group, we examined whether perceptions differed by type of mobility-assistive device (selected findings in Figure 3.3; full results in Appendix B, Table B.5). Manual wheelchair users (n = 13) were compared with powered wheelchair users (including manual wheelchairs with power add-ons; n = 12) using the Mann–Whitney U test.

Significant differences were observed for four barrier elements: crossing surface problems, high kerbs, shared spaces between pedestrians and other vehicles, and tram tracks at crossings. Manual wheelchair users generally rated three of these barriers as more severe, whereas powered wheelchair users rated high kerbs as more severe. No statistically significant differences were observed for facilitators.

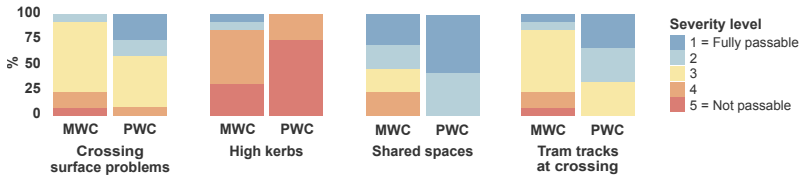


Figure 3.3: Perceived severity of barriers that showed a significant difference by type of mobility-assistive device among mobility-impaired participants. Stacked bar charts show the percentage distribution of perceived severity levels (1 = fully passable; 5 = not passable) for manual wheelchair (MWC) and powered wheelchair users (PWC).

3.4.3.2 Gender

Overall, female participants tended to rate barriers as more severe than male participants, although the magnitude and consistency of these differences varied across groups (Figure 3.4). Gender-related differences were minimal among individuals with mobility impairments and visual impairments, with only one microscale street element per group showing statistically significant differences. In contrast, more pronounced gender differences were observed among older adults and participants with situational mobility restrictions, for whom females consistently assigned higher severity ratings to several barriers, particularly those related to pedestrian crossing elements, sidewalk surface quality, and changes in level (e.g., stairs and high kerbs).

For facilitators, statistically significant gender differences were observed only within the situationally restricted group. In this group, female participants rated several microscale street elements as more facilitating for daily mobility than male participants (Figure 3.5). Full results of the Mann–Whitney U tests are reported in Appendix B, Table B.6.

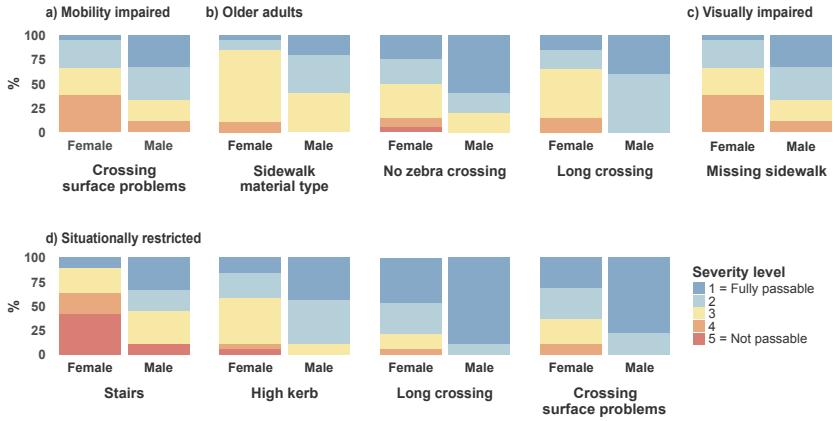


Figure 3.4: Gender differences in perceived severity of barriers that showed a significant difference across population groups. Panels show results for (a) mobility-impaired individuals, (b) older adults, (c) visually impaired individuals, and (d) situationally restricted individuals. Stacked bar charts display the percentage distribution of severity ratings (1 = fully passable; 5 = not passable) for barriers showing significant differences between female and male participants.

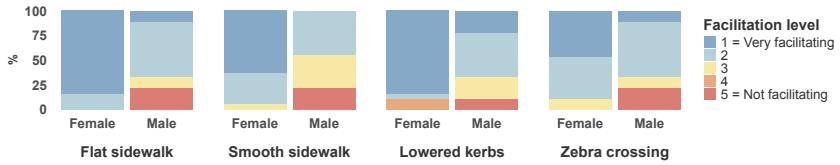


Figure 3.5: Gender differences in perceived facilitation of elements that showed a significant difference among individuals with situational restrictions. Stacked bar charts display the percentage distribution of facilitation ratings (1 = very facilitating; 5 = not facilitating) for elements showing significant gender differences between female and male participants.

3.4.3.3 Age

Age-related analyses revealed relatively few significant associations between age and perceived barrier severity or facilitator helpfulness (selected findings in Table 3.3; full results in Appendix B, Table B.7). Most age-related effects were observed within the situationally restricted group. Where significant associations were present, older participants tended to rate barriers as more severe and facilitators as more helpful. An exception was observed among visually impaired participants, for whom older individuals perceived the absence of zebra crossings as less severe.

3.4.4 Perceptual influences on movement and accessibility

Routing analyses incorporating group-specific perception profiles revealed substantial between-group variation in computed pedestrian routes. Differences in route length or impedance cost, calculated based on the presence of microscale street elements and group-specific needs, were observed for approximately 75% of origin–destination pairs. The largest difference in route

Table 3.3: The top five Spearman correlations (ρ) between participants' age and perceived severity of microscale barriers and facilitation level of microscale street elements, presented separately for each population group. Full results are reported in Appendix B, Table B.7.

Microscale street element	ρ	p-value
Mobility-impaired individuals		
Separated pedestrian space	-0.371	0.043
Stairs	-0.355	0.055
Steep sidewalk	0.355	0.055
Accessible signals at intersection	-0.306	0.100
Adequate street lighting	-0.273	0.145
Mobility restricted individuals above 65 years old		
Places to rest	-0.379	0.039
Adequate street lighting	-0.353	0.055
High kerb	-0.316	0.102
Stairs	-0.286	0.126
Steep sidewalk	-0.242	0.198
Situationally restricted individuals		
Tram tracks at crossing	0.431	0.017
Faded zebra crossing paint	0.420	0.021
Sidewalk material type	0.414	0.023
Uneven sidewalk	0.386	0.035
Zebra crossing surface problems	0.381	0.038
Visually impaired individuals		
No zebra crossing	-0.365	0.043
Cross-slope	0.334	0.066
Sidewalk material type	0.321	0.079
Accessible signals at intersection	0.319	0.080
Lack of places to rest	0.310	0.090

length, approximately 1.8 km, occurred between the mobility-impaired and visually impaired groups. Figure 3.6 presents an illustrative example of a single origin-destination pair, where routes for all four population groups are depicted. However, across all computations, the most pronounced routing disparities were consistently observed between these two groups, whereas routes generated for mobility-restricted older adults and situationally restricted individuals were more similar to those generated for visually impaired participants.

Compared with the route generated for visually impaired individuals, the route for mobility-impaired individuals avoids the old town area of the study area, where barriers are more densely concentrated and slopes are steeper. Furthermore, the route avoids high kerbs (Figure 3.6, Label 1), cobblestones (Label 3), and sidewalk obstacles such as parked cars (Label 4). Routes computed for visually impaired and situationally restricted individuals largely overlap, differing only marginally along a short segment due to obstacles such as outdoor dining areas (Label 7). In contrast, routes computed for mobility-impaired individuals and mobility-restricted older adults differ substantially, with longer, spatially distinct paths. Although the routes generated for mobility-impaired individuals and older adults are similar, they still diverge due to barriers such as shared spaces (Label 2), construction sites (Label 5),

or cobblestone surfaces (Label 6). The largest deviation, however, remains between the mobility-impaired and the visually impaired groups, as mentioned above. This example highlights how differences in the perceived impact of microscale street elements can lead to markedly different routing outcomes, even when routes are computed on the same underlying pedestrian network and for identical origins and destinations.

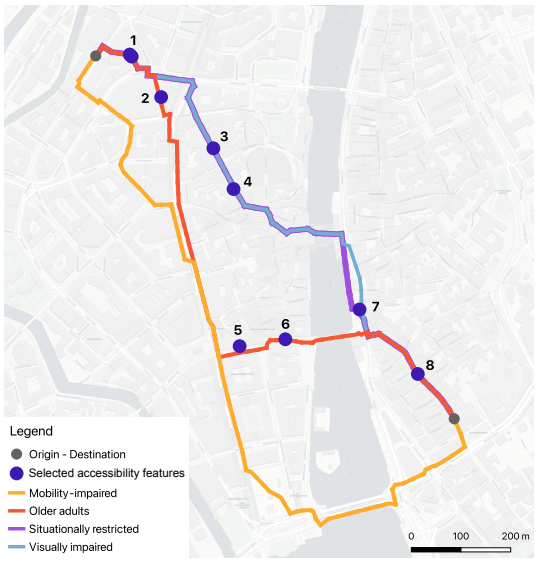


Figure 3.6: Pedestrian routes between an address point and a supermarket were computed for the four population groups using group-specific perception weights. All routes are calculated on the same enriched pedestrian network.

3.5 Discussion

3.5.1 Between-groups heterogeneities

The findings of our survey indicate that microscale street elements are perceived differently depending on the type of mobility restriction or impairment experienced (Figures 3.1 and 3.2), consistent with previous research (Li et al., 2025; Wazani et al., 2021). However, this study extends existing work by including a broader range of population groups and by capturing the degree to which elements are experienced as severe or facilitating. This provides more nuanced insight into how specific microscale street elements shape accessibility outcomes across groups.

The differences captured in our study did not always take the form of contrasting perceptions. Building on prior research that primarily focused on binary distinctions for barriers and facilitators (Rosenberg et al., 2013; Wazani et al., 2021), this study advances existing work by capturing variation in the perceived strength of these effects. In some cases, differences were clearly polarised, such as perceptions of stair severity, where the majority of visually impaired participants considered stairs passable or fully passable, while most mobility-impaired individuals rated them as not passable. In other cases, differences reflected variation in the degree of severity or facilitation, with perceptions moving in the same direction, but one group rating an element as significantly more severe or more facilitating than the other. These

patterns likely reflect how different impairments interact with microscale street elements. Features such as stairs create absolute physical constraints for mobility-impaired individuals, limiting access altogether, while remaining navigable for visually impaired individuals, resulting in polarised perceptions. In contrast, elements such as sidewalk condition or the presence of obstacles impose challenges across groups, but with varying levels of physical effort required, leading to differences in perceived severity rather than fundamentally opposing evaluations. Thus, these patterns show that accessibility challenges are shaped not only by whether an element is perceived as a barrier or facilitator, but also by the degree to which it is experienced as impeding or facilitating. At the same time, some microscale street elements, such as the lack of places to rest, the presence or absence of zebra crossings, or adequate street lighting, were perceived similarly across groups, indicating between-group similarities.

The greatest differences in perceptions across all barriers and facilitators were observed between mobility-impaired and visually impaired individuals (Figures 3.1 and 3.2), likely reflecting the differences in sensory and mobility capacities between the two groups. The magnitude of this difference may also be influenced by the fact that other population groups share characteristics with either group, such as the use of similar mobility-assistive devices, reliance on caregivers, or the experience of age-related mobility or visual limitations. In addition, mobility-impaired individuals also differed considerably from situationally restricted individuals, suggesting that the permanence of a mobility impairment may shape how strongly microscale street elements are perceived as impeding or supportive. These differences often reflected variation in the degree of perceived impact rather than opposing perceptions, with mobility-impaired individuals consistently rating elements as more impactful.

In contrast, comparatively few perceptual differences emerged between older adults with mobility restrictions and other population groups (Figures 3.1 and 3.2), reflecting the pronounced within-group heterogeneity of older adults. Participants exhibited a wide range of mobility capacities and assistive device use, from walking sticks and white canes to rollators and wheelchairs. Because older adults shared characteristics with multiple groups, their perceptions often overlapped rather than forming a distinct profile. For example, approximately one-third of older adults reported using wheeled mobility aids (Table B.2), which may explain similarities with mobility-impaired individuals.

This within-group heterogeneity aligns with previous research (Rosenberg et al., 2013), which highlights the wide spectrum of mobility capacities among older adults, from highly mobile individuals to those with multiple overlapping impairments. Although participants self-selected their population group and older adults are commonly treated as a distinct category, all groups in this study included individuals aged 65 and older (Table B.2). The key distinction was that participants in other groups identified with a specific impairment, whereas older adults attributed mobility restrictions primarily to ageing. In contrast to existing research (Harris et al., 2015), relatively few age-related differences were identified, which may reflect the classification approach adopted, and alternative grouping strategies could yield different age-related patterns.

Regarding perceptions of microscale street elements across population groups, elements classified as barriers exhibited substantial disagreement (Table 3.1 and Figure 3.1). Notably, only the absence of zebra crossings and resting places was consistently perceived as posing

relatively low difficulty across all groups, suggesting that elements actively hindering movement may exert a stronger influence on spatial accessibility than the absence of facilitating elements. For facilitators, although perceptions differed across groups for most elements, these differences were fewer and less pronounced than those observed for barriers (Table 3.2 and Figure 3.2). Elements such as wide or smooth sidewalks appear to facilitate mobility for a broad range of individuals, regardless of specific limitations, suggesting that some facilitating features function as baseline requirements rather than group-specific enablers.

Overall, the results regarding between-group variation demonstrate that perceptions of microscale street elements vary significantly across population groups and that these elements shape spatial accessibility differently depending on individuals' mobility capacities. Although most of the time perceptions are not contradictory but vary in their degree of severity or facilitation, this highlights the importance of capturing these differences rather than relying on simple barrier–facilitator distinctions. Furthermore, barriers tend to show greater differences across groups than facilitators, suggesting that elements hindering movement play a stronger role in shaping accessibility.

3.5.2 Within-groups heterogeneities

While the effects of assistive device use were examined only among mobility-impaired participants, age and gender influenced perceptions of microscale street elements in some instances across all population groups. Increasing age was associated with both higher perceived barrier severity and higher perceived levels of facilitation (Table 3.3), suggesting greater sensitivity to street elements among older individuals.

Gender-related differences also followed a consistent pattern, with females generally perceiving barriers as more severe than males across all groups (Figure 3.4). Among situationally restricted individuals, females also perceived facilitating elements as significantly more supportive (Figure 3.5). However, as females were overrepresented in the sample (approximately two-thirds of participants), these findings should be interpreted in light of the sample composition.

Despite these effects, relatively few features exhibited statistically significant perceptual differences across assistive device use, age, and gender, indicating that these characteristics play a secondary role, compared with mobility capacity, in shaping perceptions of the street environment. This contrasts with previous studies (Bredmose et al., 2023; Harris et al., 2015), which reported greater within-group heterogeneity, possibly because of focusing on a single population group, allowing finer-grained within-group variation to be detected. Nevertheless, studies including multiple population groups within a common analytical framework remain essential for enabling direct between-group comparisons and contextualising within-group variation.

The situationally restricted group exhibited the greatest variation in perceptions when accounting for age and gender (Figures 3.4 and 3.5; Table 3.3). This group encompasses a wide range of mobility restrictions, including parents with pushchairs and caregivers of individuals with varying impairments. However, the lack of detailed information enabling further sub-classification limits deeper interpretation of these differences. As situationally

restricted individuals have received limited attention in accessibility research, future studies should examine this population group in greater detail, particularly by distinguishing between different types of situational mobility restriction.

Within the mobility-impaired population, the largest perceptual differences were associated with the type of assistive device used (Figure 3.3), while differences related to age and gender were relatively limited. This pattern is consistent with findings reported by Li et al. (2025), which emphasise the central role of assistive device requirements in shaping perceived accessibility, but contrasts with Harris et al. (2015), who identified more pronounced perceptual differences between younger and older wheelchair users. This discrepancy may reflect differences in study design, sample composition, or analytical focus, suggesting that age-related effects may be context- or group-specific.

Overall, these findings show that within-group variation in perceptions of microscale street elements differs across population groups. Variation is greatest among situationally restricted individuals, reflecting the heterogeneous and context-dependent nature of their mobility constraints. In contrast, differences within mobility-impaired and visually impaired groups are more limited and more strongly shaped by factors such as assistive device use. While age and gender influence perceptions in some cases, their role remains secondary compared with mobility capacity.

3.5.3 Perceptual influences on movement and accessibility

Integrating individual perceptions into an enriched pedestrian network with accessibility attributes for routing purposes indicates that between-group differences in computed accessible routes are influenced not only by physical network constraints but also by how microscale street elements are perceived. These perceptual differences were reflected in the modelled routing outcomes and extend earlier work (Li et al., 2025) by incorporating additional microscale street elements and a more diverse participant sample.

This approach goes beyond existing accessibility models and applications, such as OpenRouteService (OpenRouteService, 2026), which also incorporate enriched pedestrian networks with accessibility features. However, these approaches typically assign uniform or predefined penalties to entire network segments. While this allows for user-specific routing, it is generally based on fixed thresholds, such as minimum width or maximum slope, and does not account for the gradual and subjective nature of accessibility. In particular, it overlooks variations in perceived passability and the relative importance of individual microscale street elements. By contrast, incorporating fine-grained, empirically derived perception weights at the level of individual street elements (Georgescu et al., 2025) enables a more detailed and realistic representation of how barriers and facilitators influence route choice.

Consistent with the Dunn test results (Figures 3.1 and 3.2), the routing analysis revealed the greatest differences between mobility-impaired and visually impaired individuals, leading to distinct routing patterns. As reflected in the survey responses, mobility-impaired individuals rated a wider range of microscale street elements as highly severe, leading to longer routes that avoid inaccessible areas. This indicates that accumulated perceptions of multiple microscale street elements can substantially reshape route choice, effectively constraining accessible

areas rather than only influencing path preference. Furthermore, these results align with existing studies showing that route selection among mobility-restricted individuals prioritises accessibility and comfort over minimising walking distance (Gharebaghi et al., 2021).

The example shown in Figure 3.6 illustrates how perception-based weights translate into routing decisions. For instance, routes for mobility-impaired individuals systematically avoid specific barriers such as high kerbs (Label 1) and sidewalk obstacles (Label 5), which, based on the survey results, are perceived as highly impassable by most participants in this group, resulting in substantial detours around the old town area. In contrast, routes for visually impaired and situationally restricted individuals are among the shortest, reflecting that these groups did not perceive the microscale street elements encountered as equally restrictive. This pattern suggests that highly severe elements do not simply increase travel cost, but can effectively prevent movement for some groups altogether, leading to detours and more fragmented routes. In contrast, elements perceived as less severe remain passable, resulting in greater overlap in routes across other groups. These differences highlight that it is not only the presence of microscale street elements, but their perceived severity across groups, that drives route divergence.

Overall, incorporating perception-based data into accessibility simulations reveals movement-pattern differences that are not captured when relying solely on physical network attributes or shortest-path assumptions. This shows that accessibility outcomes can vary substantially even within identical network structures, depending on how microscale street elements are perceived. As a result, models that treat pedestrians as homogeneous individuals risk underestimating accessibility inequalities, whereas integrating perception-based weights provides a more nuanced and equitable representation of accessibility.

3.5.4 Limitations

While this study's findings provide valuable insights into how individuals with varying mobility capacities perceive microscale street elements, several limitations should be acknowledged.

First, the analysis relies on self-reported assessments collected through an online survey rather than direct observation or experimental measurement. As a result, responses may be influenced by recall bias and subjective interpretation of survey questions, whereas other methods, such as go-along interviews, can capture more context-dependent perceptions (King & Woodroffe, 2017). However, given the aim of capturing perceptions of both facilitating and impeding microscale street elements across individuals with diverse mobility restrictions, on-site data collection would require substantially greater effort and could impose additional burden on participants. Online surveys, on the other hand, enable large-scale data collection and systematic comparison of perceived accessibility issues across diverse mobility groups.

A further limitation is the sample size, which constrained the extent of some analyses, particularly within-group differences. Despite extensive recruitment efforts, participant availability remained limited. Although the overall sample size is comparable to, and in some cases larger than, those reported in related studies (Cushley et al., 2022; Jenkins et al., 2015; Park & Chowdhury, 2018), distributing participants across four population groups reduced the reliability of more fine-grained within-group comparisons, which were therefore addressed in an exploratory manner.

Finally, the results are context-dependent, reflecting the specific pedestrian environment and participant sample examined, and may not be directly generalisable to other urban or cultural contexts. Nevertheless, the methodology is transferable to other study areas, and the findings are broadly consistent with, and in various ways extend, existing research, advancing understanding of how the built environment differentially shapes accessibility for mobility-restricted individuals.

3.6 Conclusions

Understanding how different individuals experience the urban built environment is critical for developing inclusive and equitable accessibility analyses that account for the diverse mobility capacities of all users. This study aimed to examine how microscale street elements are perceived by individuals with varying mobility capacities and to assess how incorporating these perceptions as weights into spatial accessibility analyses can yield meaningful insights. Using a comprehensive online survey, we identified differences in how microscale street elements are perceived across four population groups: mobility-impaired individuals, visually impaired individuals, situationally restricted individuals, and mobility-restricted individuals aged 65 and older.

Our findings highlight why accessibility studies should consider a more diverse mobility landscape rather than assuming equal opportunities for all users. By demonstrating that the same microscale street elements can be perceived as barriers by some groups and as neutral or facilitating by others, this study highlights the limitations of existing accessibility assessments that often treat street elements as uniformly impeding or facilitating. Incorporating user-centred, perception-based data into accessibility analyses provides a valuable means of identifying which microscale street elements disproportionately affect specific groups, alongside more conventional infrastructure-based measures.

Future research should build on this work by further investigating within-group differences associated with individual characteristics, including not only age, gender, and assistive device use, but also personal experience and levels of physical fitness. In addition, future studies should integrate perception-based data with observed mobility behaviour and enriched pedestrian network information to provide a more comprehensive understanding of spatial accessibility. Extending the analysis to different urban contexts and larger spatial scales would further clarify how microscale street elements influence mobility under diverse conditions. Together, these efforts can support more equitable and inclusive accessibility assessments, ultimately informing evidence-based urban planning and policy and contributing to the development of urban environments that better accommodate diverse mobility needs and reduce accessibility-related inequalities.

4

Developing enriched pedestrian networks with accessibility information

Chapter Outline

This chapter is adapted from the following conference paper:

Georgescu, A. I., Allahbakhshi, H., & Weibel, R. (2025). Developing enriched pedestrian networks using accessibility features. *AGILE GIScience Series*, 6, 23. https://doi.org/10.5194/agile-giss-6-23-2025

Supplementary material can be found in Appendix C.

Scope: This study introduces a workflow to integrate different detailed accessibility information, such as barriers and facilitators for pedestrian mobility, with sidewalk data to create an enriched pedestrian network.

Approach:

- Preprocessed and segmented pedestrian network data to create a consistent representation of sidewalks and intersections.
- Integrated and reclassified fine-grained accessibility data from multiple sources, including point-based features and continuous measurements such as width and slope.
- Clustered accessibility features using a two-step GDBSCAN approach to aggregate duplicate observations and preserve key attributes.
- Mapped accessibility features to network segments and computed segment-level impedance scores based on feature type, severity, width, and slope.
- Applied the enriched network to a wheelchair user profile to showcase its applicability and assess accessibility patterns and network connectivity.

Key insights:

- Integrating fine-grained accessibility features into pedestrian networks reveals substantial spatial variation in accessibility that is not captured by standard network representations.
- Accessibility barriers are unevenly distributed across the network, leading to clusters of high impedance that can restrict movement and isolate parts of the network.
- Even a relatively small proportion of inaccessible segments can significantly affect overall network connectivity for mobility-restricted users.

- Enriched pedestrian networks enable the identification of areas where accessibility is constrained, supporting more targeted interventions in urban planning.

Contributions of the PhD candidate: The PhD candidate designed and implemented the study, processed and integrated the accessibility datasets, developed the enriched pedestrian network, and drafted the manuscript.

CRediT Authorship Roles: Alexandra-Ioana Georgescu: Conceptualisation, Methodology, Software, Formal analysis, Writing – original draft, Writing – review & editing, Visualisation. Hoda Allahbakhshi: Conceptualisation, Methodology, Writing – review & editing, Supervision, Funding acquisition. Robert Weibel: Conceptualisation, Methodology, Writing – review & editing, Supervision, Funding acquisition.

4.1 Introduction

Ensuring equitable and adequate access for all to public facilities in urban areas is an essential target included in various Sustainable Development Goals, such as 10 and 11 (United Nations, 2022). This is especially important since by 2050 it is projected that approximately two-thirds of the world's population is expected to reside in urban areas (United Nations, 2019), and currently 16% of the global population worldwide is believed to live with some sort of disability (World Health Organization, 2022).

Spatial accessibility refers to how easily destinations, such as public facilities, can be reached through movement in physical space (Allahbakhshi, 2023). It is highly context-dependent and influenced by various factors (Lid & Solvang, 2016), including microscale street elements such as poles, stairs, cobblestones, kerb ramps, or pedestrian signals. These elements can either restrict or facilitate pedestrian movement, significantly impacting access to certain areas and services (Hammel et al., 2015) and contributing to social exclusion (Svensson, 2010).

Physical barriers are especially important for individuals with mobility restrictions, as they can increase perceived distance (Vale et al., 2017), reduce the number of available opportunities (Achuthan et al., 2010) and force individuals to stay at home or in familiar places (Mao & Chen, 2022). Additionally, as individuals have different mobility needs, the impact of these elements varies (Georgescu et al., 2024). For example, a high kerb may be a barrier for a wheelchair user but can serve as a facilitator, marking the edge of the sidewalk, for a visually impaired individual. Therefore, such elements become vital in assessing spatial accessibility.

However, despite their significance, research on microscale elements and their impact on individuals with varying mobility capacities remains limited. Most of these studies rely on field visits to collect data on the various accessibility features that affect pedestrian movement. These features are then recorded in spatial databases, where each element is linked to its corresponding sidewalk segment (Achuthan et al., 2010; Beale et al., 2006; Kasemsuppakorn & Karimi, 2008; Sobek & Miller, 2006). These databases can then be used to analyse the impact of these microscale elements on the mobility of different population groups (Achuthan et al., 2010; Tajgardoon & Karimi, 2015). Additionally, some studies involve different population groups in these field visits (Šakaja et al., 2019). This approach allows researchers to collect more detailed data beyond the location of accessibility features, such as the difficulty of overcoming obstacles and the overall passability of sidewalk segments. However, digitising each element and assigning it to a sidewalk segment is highly time-consuming and resource-intensive. This challenge becomes even greater when scaling up the workflow from small areas, like university campuses (Kasemsuppakorn & Karimi, 2008; Sobek & Miller, 2006), or small-town centres (Achuthan et al., 2010), to larger urban areas. Some studies take an alternative approach, estimating the minimum clear width of the sidewalk based on obstacle location and size (Vale et al., 2017), facilitating automated large-scale assessments. While effective in identifying inaccessible areas, this method does not explain the underlying causes of inaccessibility.

Building on the above, we present a unique approach to integrate multiple datasets regarding accessibility features and enrich a pedestrian network, considering both the position and the impact these features have. This network will serve as a basis for future studies into the impact of these microscale street elements on the accessibility of different individuals.

4.2 Data

Our study focuses on District 1 (the inner city) of Zürich, Switzerland. Data containing the bicycle and pedestrian pathways was downloaded from the Open Data Zürich portal (Open Data Zürich, 2022). To enrich these data with accessibility information, two datasets from ZüriACT (Allahbakhshi, 2023), a citizen science project, were used:

- One dataset included the location of over 8,800 accessibility features, such as kerb ramps, obstacles, surface problems, pedestrian signals, crosswalks, missing kerb ramps, and areas with no sidewalks. Each feature contains tags, giving further details on its type, condition, and a severity level from 1 (fully passable) to 5 (not passable). See Table C.1 in Appendix C for a detailed breakdown of feature types.
- The second dataset included over 10400 width and slope measurements of the sidewalk, collected using the Infra3D web-based tool (infra3D Web-Client, 2025). The features are represented by line data and were measured across the sidewalk for the width and along the sidewalk for the slope.

A detailed description of the point dataset, including its collection process and contents, is provided in Allahbakhshi and Ardüser (2024). Both point and line datasets were validated by a team of experts with updated imagery using the infra3D web-based tool (infra3D Web-Client, 2025).

Additionally, the swissALTI3D Digital Elevation Model (DEM) from swisstopo the Federal Office of Topography (2017), with a 0.5m resolution, was used to fill gaps in sidewalk slope data. For sidewalk width, more fine-grained data, generated every 1 meter from official survey data provided by Open Data Zürich (2021), was utilised (Allahbakhshi & Harrafamoughin, 2025).

4.3 Methods

The workflow was divided into three steps: preprocessing the pedestrian pathways data; reclassifying and clustering accessibility features before integrating them with the network segments; and calculating an impedance score for each network segment.

4.3.1 Preprocessing of pedestrian network

The sidewalk data was filtered to exclude bicycle paths and paths inside train stations or green spaces. To align segments with intersections, line geometries were dissolved and split at intersection points in QGIS. Regular segmentation was applied every 20 meters. Segments were then classified as sidewalks or intersections using ZüriACT crosswalk data. For unmarked crossings, new intersection segments were created in QGIS and added to the network.

4.3.2 Preprocessing of accessibility features

Features present in the dataset but irrelevant for the study, such as uncategorised features, were removed. The remaining features were then reclassified (Table C.2 in Appendix C). Since the ZüriACT data was collected by multiple individuals, some features were recorded multiple times, either by the same person from different angles or by different users. To aggregate points representing the same feature, the data was clustered in two steps using the generalised DBSCAN (GDBSCAN) method (Sander et al., 1998), as this can consider both spatial and non-spatial attributes (Figure 4.1). In the first step, clusters were formed based on the user ID and feature type attributes of each data point. Their centroids were then clustered again, considering only the feature type. Each centroid inherited the feature type, median severity level, and the most frequent tag from its clustered points. To include features recorded only once, the minPts parameter was set to 1. The eps parameter varied by feature type, as different types had different spatial distributions. The values were determined empirically by iteratively computing clusters at different eps values and visually analysing the results. The final clustered dataset was split into sidewalk and intersection features, which were then mapped to the nearest segment within a 10-meter buffer.

To assign width and slope measurements to sidewalk segments (no measurements were assigned to intersection segments), the centre point of each measurement line was mapped to the nearest segment. Due to regular segmentation and data distribution, some segments received multiple measurements, while others received none. In cases with multiple measurements, the narrowest width and steepest slope were used. If the segment was missing any measurements, the slope was derived using DEM data, while the width was aggregated for every segment from the fine-grained data (Allahbakhshi & Harrafamoughin, 2025). If any segment still lacked a width, it was assigned a standard width of 1.80m, following accessibility regulations, as these segments typically belonged to open pedestrian spaces.

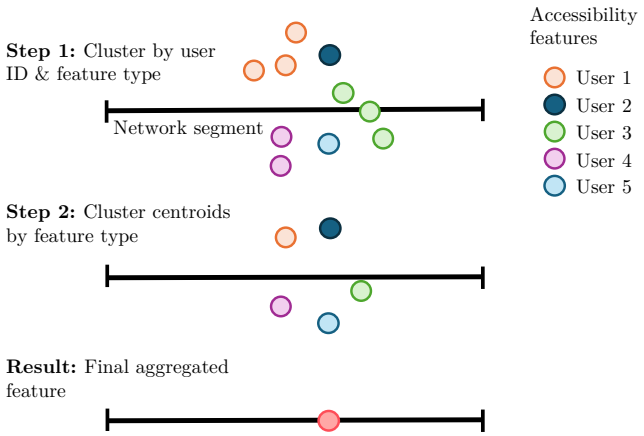


Figure 4.1: The two-step clustering process exemplified for a subset features of the same type. First, the features collected by the same user, illustrated by colour, are clustered together and the centroid of the cluster is kept. Second, all features of the same type that fall into the specific distance threshold are clustered together.

4.3.3 Impedance score calculation

An impedance score was assigned to each sidewalk and intersection segment based on its accessibility features and their severity level, width, and slope. To illustrate how the enriched pedestrian network can visualise the impact of accessibility features on individual mobility, for the purposes of this paper, we modelled a wheelchair user's profile. Since features were ranked on a 1-to-5 scale to reflect passability, width and slope were similarly categorised (Table 4.1) using the current Swiss accessibility regulations (Schweizerischer Verband der Strassen- und Verkehrsfachleute, 2015) from the perspective of wheelchair users. Considering the general width of a wheelchair, segments with a width smaller than 1 meter were considered impassable.

Table 4.1: Width and slope values categorised into severity levels.

Severity	**Width (m)**	**Slope (%)**
0	> 1.80	< 1
1	$1.6 \leq$ width < 1.8	$1 \leq$ slope < 2
2	$1.4 \leq$ width < 1.6	$2 \leq$ slope < 3
3	$1.2 \leq$ width < 1.4	$3 \leq$ slope < 4
4	$1.0 \leq$ width < 1.2	$4 \leq$ slope < 6
5	width < 1.0	≥ 6

The severity scores were normalised from (1,2,3,4,5) to (0.2,0.4,0.6,0.8,1) for barriers and (-1,-0.8,-0.6,-0.4,-0.2) for facilitators. The sign indicates the impact of the feature on the score: barriers (positive sign) increase impedance, while facilitators (negative sign) reduce it. The final segment score was calculated by summing the severity levels of all features, including width and slope. Segments with stairs, missing kerb ramps, impassable features, or that were too narrow or too steep, are considered fully inaccessible. This allows us to generate a wheelchair-suitable network for comparison with the original.

4.3.4 Data and software availability

Nearly all data used in this study is open source. The raw ZüriACT dataset is accessible via the Open Data Zürich portal (Open Data Zürich, 2024), however, it does not include width and slope measurements in its current form. The finalised dataset is undergoing quality assurance and will be released in the future. The analysis was done in R (Version 4.3.2) with a few steps done in QGIS (Version 3.34.1-Prizren). The code is not publicly available at this time due to ongoing project development, but it can be provided upon request.

4.4 Results

After preprocessing, the new pedestrian network contained 4492 segments with a maximum length of 20 meters.

The accessibility features from the ZüriACT dataset were reclassified into 12 new feature types (Table 4.2). This reclassification was done to better categorise more similar features (i.e., distinguishing between smaller or larger obstacles) or to distinguish between more and less impactful features (i.e., considering steps and stairs as Height Difference in their

own category). The original category Surface Problem was divided into Surface Material Type and Surface Condition, which show locations where either the sidewalk material or its condition were considered to impede movement. The clustering results, as well as the eps variable used for each clustering step, can also be found in Table 4.2.

Table 4.2: Clustering results and eps choice for each feature type

Feature Type	**1st Clustering**		**2nd Clustering**	
	No.	**eps**	**No.**	**eps**
Kerb Ramp	2560	2	2141	3
No Kerb Ramp	61	2	55	3
Pedestrian Signal	935	2	724	3
Crosswalk	1154	2	986	6
Height Difference	173	7	139	10
Large Scale Obstacle	266	7	236	8
Small Scale Obstacle	428	2	359	4
Surface Condition	163	5	148	5
Surface Material Type	2469	5	2063	7
No sidewalk	65	7	63	10
Sidewalk ends abruptly	33	7	31	10
Shared Space	306	7	262	10

Using GDBSCAN in a two-step manner, we identified 1,380 clusters in the accessibility features data and 2,218 unique features that were only collected once. The average size of the clusters was 4.63 features, with a maximum size of 53 features. The most clustered feature types were Kerb Ramp (n = 416), Surface Material Type (n = 392), Pedestrian Signal (n = 156), and Crosswalk (n = 148). After clustering, each cluster was represented by its centroid, and the final accessibility features dataset was formed, including the unique features. Figure 4.2 illustrates the distribution of accessibility features after clustering.

The spatial distribution of the computed impedance score for a wheelchair user, per each pedestrian segment, can be viewed in Figure 4.3. Each sidewalk and intersection segment is coloured by its impedance score. After integrating all accessibility features, the width, and the slope information, 27% of the segments were found to have an impedance score of 0, being fully accessible. 34% of the segments were found to contain at least one accessibility feature with almost three-quarters of that containing at least one barrier. Only around 9% of the segments showed increased suitability due to facilitators when compared to segments with no accessibility features. These segments, represented by scores below 0, can mainly be found distributed around intersections, as the only facilitators included were features such as kerb ramps, crosswalks, and pedestrian signals. Scores above 0 reflect the presence of barriers that increase the impedance of the segment. The areas with the highest impedance scores are mainly the pedestrian areas inside District 1, where the old town can be found. As shown in Figure 4.2, this area features shared pedestrian spaces, cobblestone paving, and steep slopes. The rest of the district exhibits close to 0 impedance scores, meaning that the segments are accessible or contain few barriers. A score of 0 denotes segments with fully accessible width and slope, free of barriers or facilitators.

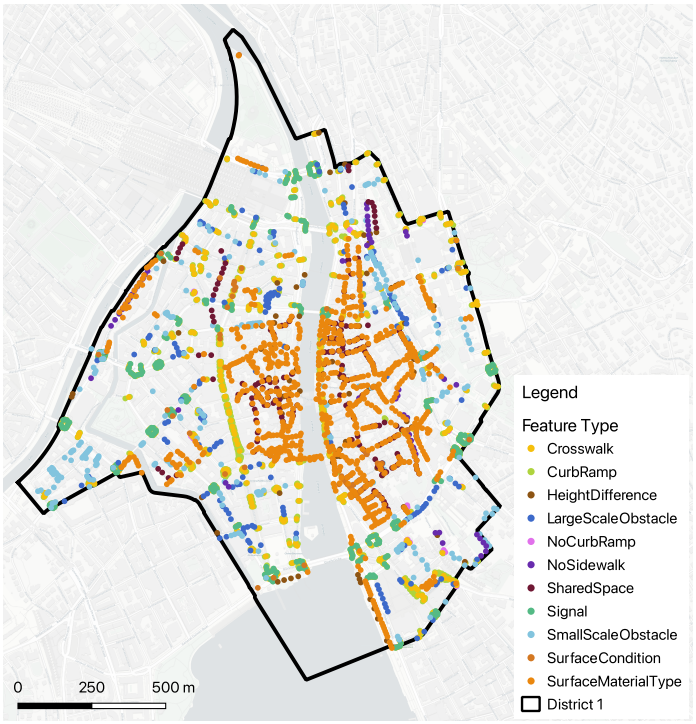


Figure 4.2: Overview of the distribution of accessibility features in the study area.

The constraints applied to the network to create a wheelchair-suitable network revealed that 17% of segments are considered inaccessible, as shown in the left-side map of Figure 4.4. These segments are primarily concentrated in the district's old town and areas with steep slopes on the right side. The right-side map illustrates how these segments affect network connectivity, leaving entire areas inaccessible to wheelchair users. Consequently, individuals in these areas would be unable to reach desired destinations independently and would have to rely on others or alternative transportation modes.

4.5 Discussion

Although accessibility features and their data availability vary from city to city, this workflow can still be a general framework for enhancing pedestrian networks, as there is systematicity in how accessibility features impact individuals with mobility restrictions (Georgescu et al., 2024). In our study, all data were integrated as point features, regardless of whether they represented discrete (e.g., poles) or continuous features (e.g., a sidewalk paved with cobblestones). This approach aligns with prior accessibility studies (Achuthan et al., 2010; Sobek & Miller, 2006). To further refine the way accessibility features were represented, clustering was applied to aggregate identical features recorded multiple times. This helped to prevent an overrepresentation of segment characteristics. The use of GDBSCAN was advantageous as it allowed the incorporation of non-spatial attributes in the clustering process; however, parameter selection, particularly the maximum distance between clustered features, eps, required careful calibration. Furthermore, in our study, only the ID and feature type were considered as non-spatial attributes, meaning obstacles with different tags (e.g., trash cans and poles) could be clustered together. Future work could refine this step by incorporating feature tags when clustering.

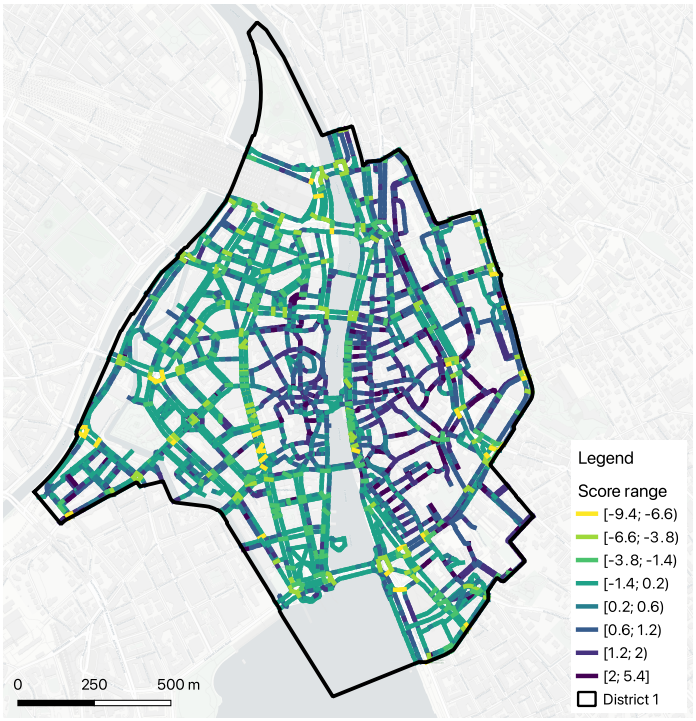


Figure 4.3: The enriched pedestrian network, segments are coloured by their impedance score, for the profile of a wheelchair user. Score range divided using natural breaks.

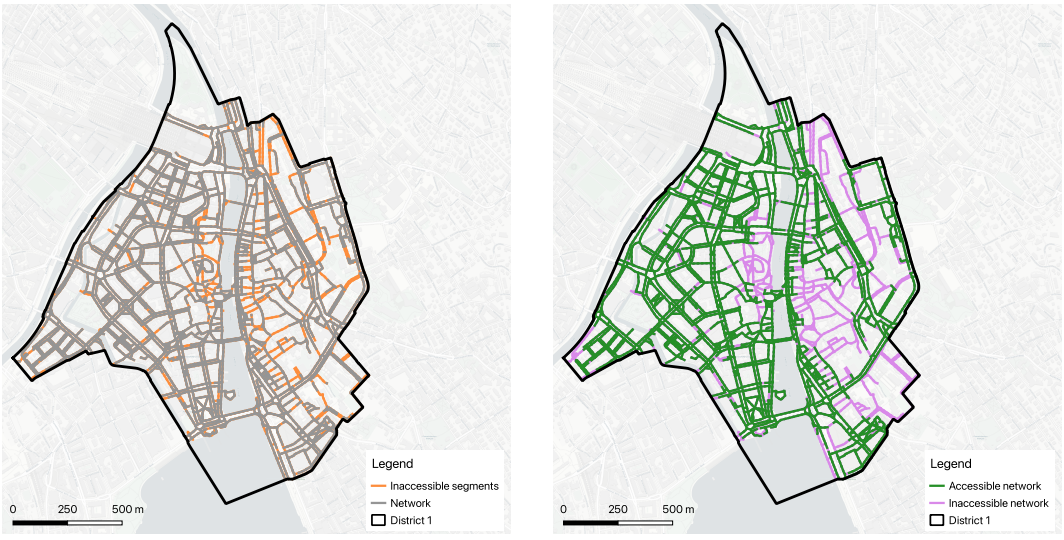


Figure 4.4: Overview of the distribution of inaccessible segments (left) and the connected accessible network left as a consequence of these segments (right).

The distribution of the calculated impedance score, characterised by negative impedance at intersections and positive impedance elsewhere, was expected given the data structure and classification used. As accessibility features were categorised into sidewalk and intersection segments, intersections predominantly contained facilitating elements, while sidewalks included only features that increased their impedance. The notably high negative impedance values observed in certain intersection segments can be attributed to the spatial clustering of facilitating elements, such as multiple kerb ramps, pedestrian signals, and crosswalks. These results contradict the findings of earlier studies that found intersection segments challenging (Šakaja et al., 2019). This may be due to a simplified representation of the network in other studies or their exclusion of facilitators, focusing solely on barriers.

Analysing the network's suitability based on specific mobility needs is one of the many instances when an enriched pedestrian network with accessibility features can be used. Our findings are consistent with existing literature, such as the work by Vale et al. (2017), which identified areas in Lisbon where sidewalk elements acted as barriers, contributing to isolation and hindering wheelchair users' access to destinations beyond these zones. Furthermore, existing studies also create various mobility profiles (Sobek & Miller, 2006; Tajgardoon & Karimi, 2015) based on which they assess the suitability of pedestrian networks. While our assumptions were based on accessibility regulations and literature, when creating this profile, in future work, real-world perception data will be added to the enriched network to further explore how different contextual factors affect accessibility for individuals with varying mobility needs. Such an enriched network can not only serve as the basis for personalised routing algorithms but also inform decision-making for initialising and prioritising interventions aimed at fostering a more inclusive urban environment.

5

Impact of microscale street elements on accessibility disparities

Chapter Outline

This chapter is adapted from the following publication:

Georgescu, A. I., Allahbakhshi, H., Harrafamoughin, A., & Weibel, R. (2026). Mind the obstacle: Impact of microscale street elements on urban accessibility disparities. *Journal of Urban Mobility*, 9, 100203. https://doi.org/10.1016/j.urbmob.2026.100203

Supplementary material can be found in Appendix D.

Scope: To explore how microscale street elements influence the spatial accessibility of individuals with different mobility capacities, and how these differences shape overall patterns of spatial accessibility.

Approach:

- Integrated fine-grained accessibility data with perception-based weights to assign segment-level impedance values reflecting the presence and perceived impact of microscale street elements.
- Modelled group-specific pedestrian networks for mobility-impaired and visually impaired individuals.
- Computed and compared accessibility patterns and accessible route characteristics across the two population groups.
- Analysed differences in route length, detours, and encountered accessibility features to identify drivers of accessibility disparities between population groups.

Key insights:

- Microscale street elements lead to unequal accessibility outcomes across population groups within the same urban environment, demonstrating that fine-grained network modelling is essential to accurately capture accessibility disparities.
- Mobility-impaired individuals experience lower accessibility due to impassable barriers that restrict movement and fragment the pedestrian network.
- Accessible routes for mobility-impaired individuals are more frequently longer and require detours to avoid impassable segments.
- Differences in accessibility arise not only from the presence of microscale street elements

but also from how population groups perceive and prioritise them.
- Individual barriers can disproportionately influence accessibility, with single features sometimes causing large detours, particularly for mobility-impaired individuals.

Contributions of the PhD candidate: The PhD candidate designed the study, collected and processed the perception data, preprocessed the other integrated datasets, designed and conducted the network enrichment, wrote the source code for and conducted the network modelling and spatial accessibility analyses, and drafted the manuscript.

CRediT Authorship Roles: Alexandra-Ioana Georgescu: Conceptualisation, Methodology, Software, Formal analysis, Investigation, Writing – original draft, Writing – review & editing, Visualisation. Hoda Allahbakhshi: Conceptualisation, Methodology, Writing – review & editing, Supervision, Funding acquisition. Alireza Harrafamoughin: Software, Data Curation, Resources. Robert Weibel: Conceptualisation, Methodology, Writing – review & editing, Supervision, Funding acquisition.

5.1 Introduction

As urban populations grow rapidly, cities are increasingly expected to ensure equitable access to public spaces and opportunities for all individuals, regardless of their physical abilities. An estimated two-thirds of the global population are projected to live in cities by 2050 (United Nations, 2019), highlighting the importance of developing inclusive urban infrastructure. Additionally, considering that roughly 16% of people worldwide live with some form of disability (World Health Organization, 2022), designing urban environments that accommodate diverse mobility needs is essential for fostering true inclusivity.

The built environment plays a crucial role in shaping active movement through urban areas, especially for individuals with mobility restrictions (Orellana et al., 2020; Vale et al., 2017). Walkable urban environments promote social equity by ensuring access to services and opportunities (Lee et al., 2017), enhancing independence (Horak et al., 2025), fostering social inclusion (Svensson, 2010), and contributing to both the physical and mental health of individuals (Lid & Solvang, 2016). However, in many cities, pedestrian infrastructure remains inaccessible to individuals with mobility or visual impairments (Cushley et al., 2022; Kapsalis et al., 2024), further exacerbating disparities between population groups (Spray et al., 2022). Features such as stairs, obstacles, and uneven surfaces can increase walking distances, render areas inaccessible, or even confine individuals to their homes or familiar areas (Achuthan et al., 2010; Mao & Chen, 2022; Vale et al., 2017). However, despite their significance, little is known about how specific sidewalk and crosswalk features impact spatial accessibility differently for individuals with varying mobility restrictions or impairments (Georgescu et al., 2024).

While traditional urban planning has focused more on macro- and mesoscale factors, such as land-use diversity, street connectivity, or facility density, studies show that microscale features can influence pedestrian satisfaction and mobility to a similar degree (Kim et al., 2014). When considering mobility or visual impairments, it becomes clear that commonly used accessibility measures, such as the shortest path, are insufficient for assessing accessibility (Gharebaghi et al., 2021). These methods often ignore contextual factors that can impact movement through space, leading to overestimates of accessibility and underestimates of inequalities (Ryan & Pereira, 2021). For example, when encountered in the urban environment, an accessibility barrier (e.g., stairs, high kerbs, or narrow sidewalks) can either cause an individual to slow down, change the route, or halt altogether (Henje et al., 2021; Prescott et al., 2021; Šakaja et al., 2019).

In this study, we explore how microscale street elements influence the spatial accessibility of individuals with different mobility capacities, and how these differences shape overall patterns of spatial accessibility. Specifically, the study focuses on features such as sidewalk width, slope, surface conditions, obstacles (e.g., vegetation, street furniture, parked vehicles), kerbs, zebra crossings, and accessible signals, which are known to impact the accessibility of individuals with varying mobility restrictions (Georgescu et al., 2024). To examine these impacts, we combined detailed data on these elements with perception data gathered through an online questionnaire, where participants with mobility or visual impairments assessed how challenging or facilitating each feature is. Using this information, we modelled the pedestrian network separately for both groups and compared accessibility patterns.

This study contributes to the literature by presenting a workflow for integrating fine-grained accessibility and perception data in spatial analyses. Additionally, it expands existing knowledge by considering multiple population groups and provides insights into how urban features affect individuals with varying mobility capacities. Finally, it offers context- and group-specific insights that urban planners can use to prioritise interventions and target improvements for a more inclusive urban environment.

5.2 Background

5.2.1 Terminology

As defined by Hansen (1959) and further developed by Litman (2017) and Lanza et al. (2023), spatial accessibility, or accessibility for short in this paper, refers to the ease with which individuals can reach potential opportunities. Reflecting on Hansen's original concept, Lanza et al. (2023) emphasise that accessibility involves not only spatial elements but also individuals' personal attributes, such as mobility capacities and preferences. Thus, this highlights that a comprehensive accessibility assessment must account for both the characteristics of individuals and the physical environment. In this regard, while mobility can generally be defined as the ability to move oneself, for example, by walking or using assistive devices (Webber et al., 2010), accessibility can be viewed as the extent to which the environment enables or constrains this movement (Tyler, 2006).

The mobility capacity of an individual, defined as the physical ability to move independently from one location to another (Tyler, 2006), may vary due to factors such as impairment, health conditions, ageing, or situational circumstances (e.g., carrying heavy luggage or a stroller), and directly shapes how they navigate urban environments (Lid & Solvang, 2016). Numerous studies have shown that individuals with varying mobility impairments or restrictions experience lower spatial accessibility than those without such limitations (Achuthan et al., 2010; Orellana et al., 2020; Vale et al., 2017). One of the main causes of this disparity is the mismatch between individuals' mobility capacities and the built environment's requirements, such as overcoming microscale street elements that may obstruct the path (Cepolina & Tyler, 2004; Tyler, 2006).

Microscale street elements, also referred to as accessibility features in this paper, are small-scale features of the pedestrian environment, belonging to sidewalks, crosswalks, or pedestrian areas. These include street furniture (e.g., benches, signs, poles), sidewalk materials and conditions (e.g., cobblestones, utility holes), stairs, or crosswalk elements (e.g., kerb ramps, tram tracks along the crosswalk, pedestrian signals) (Millstein et al., 2013). Such elements may act as barriers (e.g., stairs, cobblestones, construction sites), obstructing movement, or as facilitators (e.g., pedestrian signals, tactile paving), supporting movement through the urban environment and helping to compensate for declining mobility capacities. Examples of how microscale street elements affect spatial accessibility include: wheelchair users unable to navigate narrow sidewalks (Kasemsuppakorn & Karimi, 2009); visually impaired people finding it challenging to navigate past newsstands, advertising signs, and tables on the sidewalk (Lid & Solvang, 2016); or older adults experiencing fatigue more quickly and lacking available seats to rest (Koon et al., 2020).

5.2.2 Related work

While numerous studies identify which elements influence spatial accessibility for different groups (Harris et al., 2015; Jenkins et al., 2015; Park & Chowdhury, 2018; Šakaja et al., 2019; Wazani et al., 2021), few quantify their impact to provide informative and actionable insights. Many have employed qualitative methods such as questionnaires (Harris et al., 2015; Jenkins et al., 2015), interviews (Park & Chowdhury, 2018), and focus groups (Šakaja et al., 2019) to capture the subjective experiences of individuals and explore which sidewalk elements are perceived as barriers or facilitators in urban environments. However, there is a lack of studies that integrate this information into quantitative accessibility analyses to understand not only what elements influence spatial accessibility but also the extent of their influence, depending on individuals' mobility capacities.

A growing body of research has begun incorporating microscale street elements into spatial accessibility analyses. For instance, Achuthan et al. (2010) assessed the number of reachable facilities, accounting for sidewalk barriers, including sidewalk width, slope, and the absence of kerb ramps and crosswalks. However, their model classifies any segment containing an obstacle as inaccessible. While this highlights challenges for individuals with mobility restrictions, it may underestimate accessibility, as not all barriers entirely block passage. Vale et al. (2017) refine this by classifying segments as inaccessible only when the remaining minimum clear width of the sidewalk falls below a threshold, thereby accounting for cases in which obstacles are present but do not restrict movement.

Introducing more nuanced approaches, Tajgardoon and Karimi (2015) rank network segments into categories from comfortable to impassable depending on the elements present on them. They expand on previous literature by considering additional accessibility-related features, including sidewalk surface condition and type, sidewalk traffic, and the number of landmarks along the route. Further, studies such as those by Lanza et al. (2023) and Jehle et al. (2024) adopt a more continuous approach, calculating a suitability score for each network segment based on the elements present. Not only do these studies include more accessibility related elements such as pedestrian friendliness, presence of obstacles and lack of lighting (Lanza et al., 2023), and separation from road of footpath (Jehle et al., 2024), but they also include elements such as diversity of POIs and land use, safety and attractiveness of public spaces as well as road elements that can influence pedestrians.

While these studies include not only the presence of the microscale street elements but also differentiate between their impact by weighting them according to different profiles (Jehle et al., 2024; Lanza et al., 2023; Tajgardoon & Karimi, 2015), they often rely on assumptions or weights derived from the literature rather than incorporating the subjective perceptions of individuals affected by such elements, and only very few focus on the difference between population groups (Jehle et al., 2024; Tajgardoon & Karimi, 2015). Furthermore, most studies that use detailed accessibility data to assess spatial accessibility focus on small study areas such as university campuses (Kasemsuppakorn & Karimi, 2009; Sobek & Miller, 2006; Tajgardoon & Karimi, 2015) or small-town centres (Achuthan et al., 2010).

In summary, research on microscale elements and their impact on individuals with diverse mobility capacities remains limited, and disparities across population groups remain largely

unexplored. Even when studies account for the diverse mobility capacities of restricted individuals, they tend to concentrate on a single population group (Achuthan et al., 2010; Beale et al., 2006; Kasemsuppakorn et al., 2015; Matthews et al., 2003; Meyers et al., 2002; Wennberg, 2009), often overlooking heterogeneities existing between different population groups. This is particularly significant, as the heterogeneity of mobility capacities both within and between population groups implies that some features may exhibit a twofold effect, where the same street element may serve as a barrier for one group and a facilitator for another (Georgescu et al., 2024). For example, a high kerb might significantly impede a wheelchair user; however, for a visually impaired individual, it could define a clear boundary between the sidewalk and the street. These different impacts highlight the importance of incorporating real-world perceptions from diverse groups in accessibility analyses. Further, given the twofold effect of accessibility features, studies focusing on a single population or mobility restriction may yield inadequate recommendations for individuals with differing disabilities (Vale et al., 2017).

Building on prior work conducted in our group, which involved a large-scale citizen science project to collect detailed accessibility data (Allahbakhshi & Ardüser, 2024; Allahbakhshi, 2023), we performed an empirical study to assess accessibility disparities arising from varying mobility capacities within a study area in Zurich, Switzerland, and enhance existing approaches in several key aspects:

(1) We propose a comprehensive methodology for fine-grained accessibility modelling, using detailed data on the location and characteristics of microscale street elements.
(2) We demonstrate the feasibility of incorporating microscale street elements into spatial accessibility with manageable effort and the added value such granular modelling brings.
(3) We allow for a more in-depth assessment of pedestrian accessibility by considering both barriers and facilitators to movement. We apply this approach across a relatively large, topographically and structurally complex urban area to highlight spatial variation in accessibility and its diverse impacts on different population groups.
(4) We calibrate our accessibility analysis using real-world perception data from individuals within those groups, assigning weights to different microscale street elements accordingly to reflect their diverse and specific needs. This approach demonstrates how accessibility models can be grounded in real-world assessments of affected population groups rather than relying on generic weights taken from the literature.
(5) We evaluate the impacts of microscale barriers and facilitators quantitatively and visually, at the aggregate district scale and the disaggregated scale of individual paths. This provides urban planners with tools to identify problem areas and pinpoint potential causes.

5.3 Materials and methods

5.3.1 Study area

Our study area is District 1 of the city of Zurich, Switzerland. This district encompasses Zurich's old town, characterised by a complex street pattern typical of medieval European cities, as well as the central business district (Figure 5.1). The topography is varied, with

relatively level terrain in the business district and rather hilly terrain with partially steep slopes in the old town. Furthermore, the district is roughly divided into two parts by a major topographic obstacle: the river Limmat. Despite the district's limited size and small resident population, approximately 5,800 people or only 1.3% of the overall population of Zurich (Stadt Zürich, 2024), District 1 includes many of Zurich's main tourist attractions, shopping amenities and public administration buildings, and hosts around 76,700, or 14%, of employees working in Zurich (Stadt Zürich, 2024), which together generate a high daytime population and a diverse range of destinations accessed daily. Moreover, large parts of the district are designated pedestrian zones, resulting in the highest pedestrian traffic volumes in the city, hence making pedestrian spatial accessibility a key factor in promoting an inclusive and equitable urban environment.

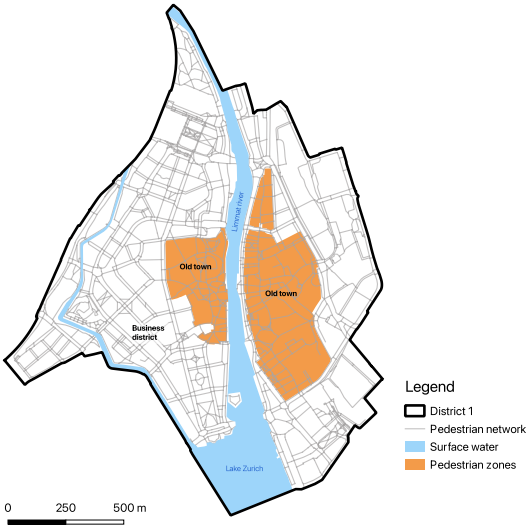


Figure 5.1: District 1 in the city of Zurich showing the pedestrian zones (orange) concentrated in the old town on both sides of the Limmat river and the business district in the western part of the district.

5.3.2 Data

An overview of the datasets utilised in this study, and their respective purposes, is provided in Table 5.1. To ensure relevance, sidewalk segments were filtered to include only pedestrian pathways, excluding those located within train stations or green spaces. The point dataset, which contains microscale street elements (Appendix D, Figure D.1), contains not only location information but also detailed attribute data. These attributes include: (a) feature type (e.g., kerb ramps, obstacles, surface problems, and crosswalks); (b) severity classification of the feature, rated on a scale from 1 (fully passable) to 5 (impassable) for barriers and on a scale from 1 (not facilitating) to 5 (very facilitating) for facilitators; (c) additional tags such as the condition of the feature (e.g., broken, uneven); (d) specific obstacle categories (e.g., poles, signs, outdoor dining areas); and (e) an indication of whether the feature is temporary (e.g., parked bicycles, vehicles, or construction sites). Due to incomplete coverage in the initial datasets for sidewalk width and slope, supplementary datasets were used to address gaps and enhance overall spatial coverage.

Table 5.1: Data sources.

Data	Purpose	Reference/source
Sidewalk segments	Used to build the sidewalk network	Open Data Zürich (2022)
Geocoded addresses, point dataset	Used for the accessibility calculations	Open Data Zürich (2025)
Location of microscale street elements	Used to enrich the sidewalk segments	Allahbakhshi and Ardüser (2024)
Sidewalk width measurements	Used to enrich the sidewalk segments	Allahbakhshi and Ardüser (2024)
Sidewalk slope measurements	Used to enrich the sidewalk segments	Allahbakhshi and Ardüser (2024)
Sidewalk width dataset generated based on cadastral data	Used to complete the width measurements	Allahbakhshi and Harrafamoughin (2025)
Digital elevation model 0.5m resolution	Used to complete the slope measurements	Federal Office of Topography (swisstopo) (2017)
Real-world individual perception of accessibility features	Used to weight the importance of the different accessibility features in the cost calculation for the segment	Primary data collected by the authors in a survey

5.3.3 Survey design and participants

In parallel with the accessibility analysis, data on subjective perceptions of accessibility features were collected through an online survey. In this survey, 62 participants evaluated various microscale street elements based on their perceived impact on daily mobility within urban environments. The elements incorporated in the survey corresponded to the features included in the accessibility analysis. Participants were eligible if they were at least 18 years old, residents of urban areas in Switzerland, and self-identified as having either a mobility or visual impairment. Although recruitment initially focused on residents of the city of Zurich, this approach could not be realised due to recruitment challenges associated with engaging vulnerable and hard-to-reach population groups, such as individuals with mobility restrictions. Consequently, the sampling frame was broadened to include residents of urban areas across Switzerland. We do not consider including participants from urban areas outside the study area a significant limitation, as Swiss urban areas are relatively homogeneous in terms of pedestrian infrastructure standards (VSS Zürich, 2015) and accessibility features.

Recruitment was conducted in coordination with various organisations that either support individuals with mobility or visual impairments or work directly with them. Additionally, participants were recruited through personal networks. The survey was divided into three parts: general information, perceptions of barriers, and perceptions of facilitators. The first part contained questions on age, gender, postal code and mobility assistive devices used. The second and third parts were the core of the questionnaire and contained questions that asked participants to rate different microscale street elements on a scale from 1 to 5, ranging from fully passable to impassable for barriers, and from very facilitating to not facilitating for facilitators. To ensure clarity and consistency, textual definitions were provided for all street elements, and images were used to illustrate them clearly.

In total, 30 individuals with mobility impairments (17 female, 10 male, 3 non-binary), aged between 22 and 65 years (M = 39.1, SD = 14.3), and 32 individuals with visual impairments (22 female, 9 male), aged between 19 and 76 years (M = 44.3, SD = 16.4), completed the survey. Of the 30 individuals with mobility impairments, 27 reported using a wheelchair (of these, 5 primarily use an electric wheelchair, and 4 typically use power add-ons with a manual wheelchair) as their primary mobility assistive device in daily life. Among the 32 visually impaired individuals, 25 reported using a white cane, and 7 reported using an assistance dog.

5.3.4 Methodology

The overall workflow for the analysis is shown in Figure 5.2. Our analysis follows four main steps, which are described in detail in the following sub-sections: (5.3.4.1) Pedestrian network enrichment, where we integrate detailed accessibility information into the pedestrian network; (5.3.4.2) Impedance Score calculation, where we develop individual profiles for our two target groups based on survey data and calculate an impedance cost for each network segment; (5.3.4.3) Accessibility patterns analysis, where we apply a routing algorithm to compute the shortest and most accessible routes for each group; and (5.3.4.4) Between-groups comparison, where we analyse and compare the resulting routes to identify key elements that hinder or facilitate accessibility for individuals with different mobility capacities.

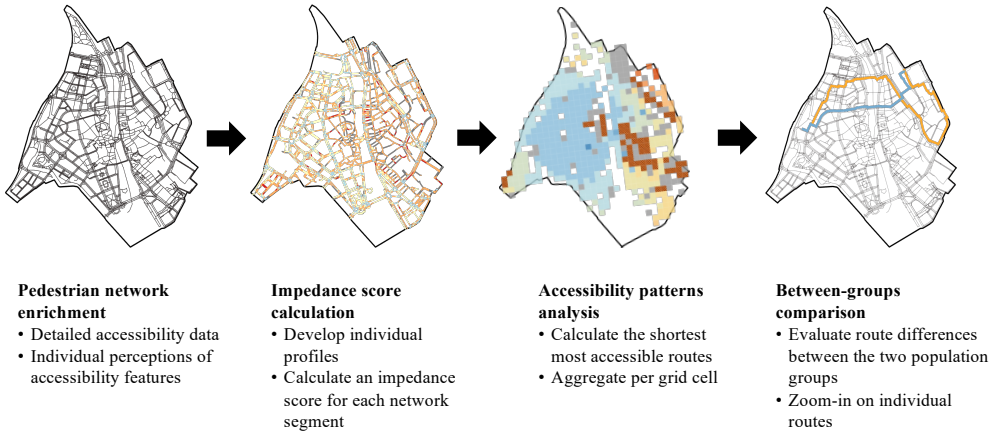


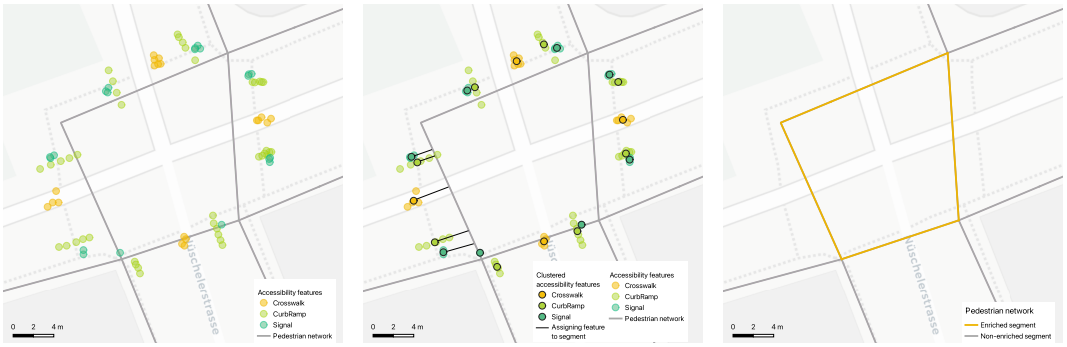
Figure 5.2: Study workflow.

5.3.4.1 Pedestrian network enrichment

The detailed workflow for enriching the pedestrian network for the accessibility analysis is outlined in Chapter 4. In brief, the pedestrian network was divided into 20-metre segments and subsequently categorised into sidewalk and intersection segments. As the accessibility features dataset was collected by multiple individuals within a citizen science project using street view imagery (Allahbakhshi & Ardüser, 2024), some features were recorded multiple times, either by the same individual from different angles or by other users. Although the data were validated by experts using updated street view imagery via the infra3D web-based tool (infra3D Web-Client, 2025; iNovitas AG, 2025), duplicate records of the same feature were retained, as they may reflect different individuals' perceptions. For our analysis, we

aggregated duplicate points representing the same feature to avoid over-representing elements collected multiple times. We applied the generalised DBSCAN (GDBSCAN) method (Sander et al., 1998) in two steps: first, clustering by participant ID; and second, clustering by feature type. The final clustered dataset was divided into sidewalk and intersection features, which were then mapped to the nearest segment within a 10-metre buffer. The buffer distance was chosen empirically, based on sensitivity analysis and literature using similar data (Li et al., 2022). A visualisation of the clustering and mapping process is shown in Figure 5.3.

Sidewalk segments were further enriched with width and slope measurements. In cases where measurements were missing, gaps were filled using additional datasets, such as digital elevation models and sidewalk width data generated from cadastral data (Table 5.1). If width data were still unavailable for a segment, a default width of 1.80 metres was assigned, in accordance with accessibility regulations (VSS Zürich, 2015). To better reflect real-world pedestrian conditions, new segments were created to represent unmarked crosswalks, i.e., areas where pedestrians commonly cross without priority, or within 30 km/h traffic zones where ad-hoc crossings are allowed. For each of these unmarked crossings, features indicating the absence of pedestrian-accessible signals were also added to the network.



(a) (b) (c)

Figure 5.3: Simplified visualisation of the enrichment workflow for the accessibility features. (a) the raw labels (b), the resulting clustered labels, and how they are mapped to the closest segment (c), segments enriched with accessibility information.

5.3.4.2 Impedance score calculation

Figure 5.4 presents an overview of the workflow used to calculate the ImpedanceScore.

In our study, we consider two types of accessibility features: barriers and facilitators. Barriers were rated on a scale from 1 to 5, where 1 indicates fully passable and 5 indicates impassable. Hence, for barriers, higher values indicate a more severe impediment. Conversely, for facilitators, an inverted scale was used, with 5 representing the strongest facilitating effect and 1 the weakest.

As the dataset used for width and slope measurements did not include severity level information, these features were categorised similarly as barriers (Table 5.2) using the current Swiss accessibility regulations (VSS Zürich, 2015), with thresholds adapted for different user groups. For mobility-impaired users, narrower sidewalks and steeper slopes were considered highly

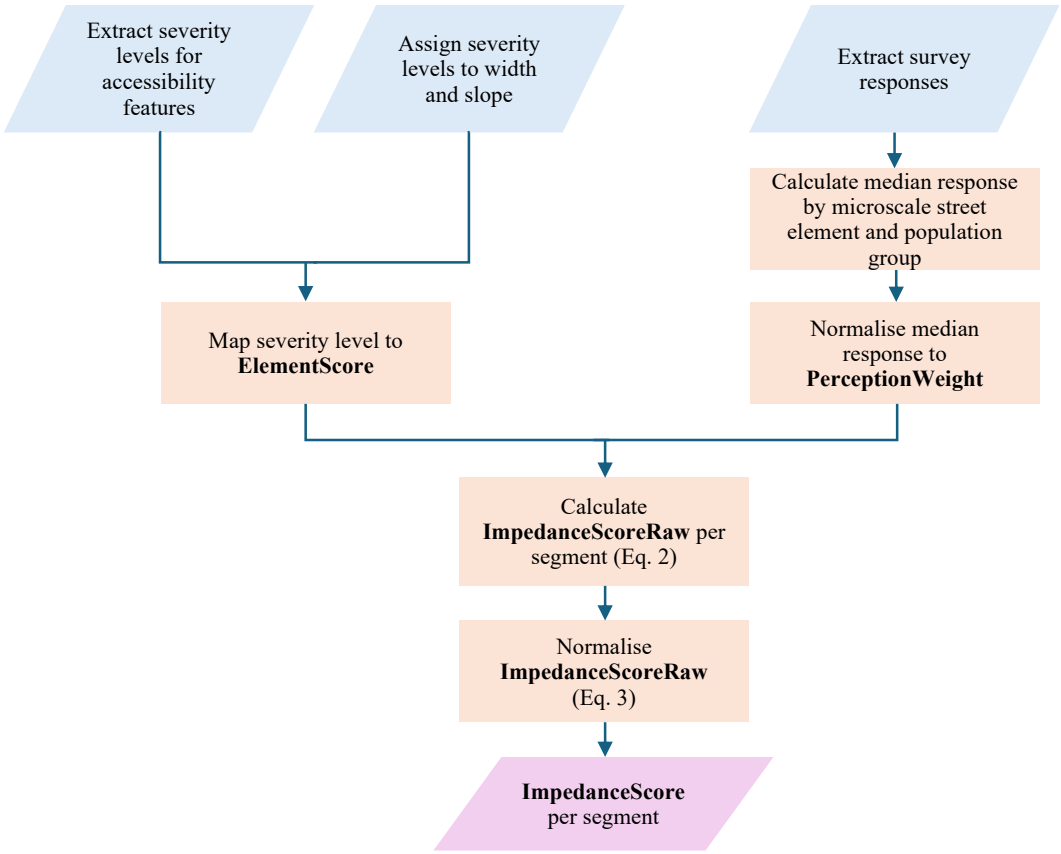


Figure 5.4: Overview of the workflow used to calculate the ImpedanceScore.

restrictive, while visually impaired users were less constrained by these conditions. These group-specific thresholds ensure that the severity level reflects the accessibility challenges relevant to each population group. The severity levels for width and slope range from 0 to 5 to ensure that fully accessible segments do not receive a misleading score. The original severity level scale for microscale street elements starts at 1, as all data points correspond to accessibility features explicitly identified by individuals as influencing accessibility (Allahbakhshi & Ardüser, 2024). A severity level of 0 was not included as the presence of a labelled feature inherently implies some degree of impact. However, using 0 for the width and slope allows segments with no barriers or facilitators and compliant width and slope to receive a score value of 0, accurately representing full accessibility.

Each feature's severity level was converted into an ElementScore. Barriers were mapped from 1,2,3,4,5 to 0.2,0.4,0.6,0.8,1 with 0.2 being fully passable and 1 impassable, and facilitators from 1,2,3,4,5 to -1,-0.8,-0.6,-0.4,-0.2 with -1 being highly facilitating and -0.2 not facilitating. This mapping approach follows prior studies using comparable data (Li et al., 2022).

To account for differences in how users perceive the importance of individual accessibility features, ElementScores were weighted using feature-specific PerceptionWeights derived from the survey data. The PerceptionWeight reflects the relative importance of each microscale street element for different user groups (Table 5.3). For each accessibility feature i and

Table 5.2: Width and slope values categorised similarly as the barrier features into 5 severity levels.

	Severity	**ElementScore**	**Mobility-impaired**	**Visually Impaired**
Width (m)	0	0	> 1.80	> 1.80
	1	0.2	$1.6 \leq$ width < 1.8	$1.6 \leq$ width < 1.8
	2	0.4	$1.4 \leq$ width < 1.6	$1.2 \leq$ width < 1.6
	3	0.6	$1.2 \leq$ width < 1.4	$1.0 \leq$ width < 1.2
	4	0.8	$1.0 \leq$ width < 1.2	$0.7 \leq$ width < 1.0
	5	1	width < 1.0	width < 0.7
Slope (%)	0	0	< 1	< 1
	1	0.2	$1 \leq$ slope < 2	$1 \leq$ slope < 2
	2	0.4	$2 \leq$ slope < 3	$2 \leq$ slope < 4
	3	0.6	$3 \leq$ slope < 4	$4 \leq$ slope < 7
	4	0.8	$4 \leq$ slope < 6	$7 \leq$ slope < 10
	5	1	slope ≥ 6	slope ≥ 10

population group p, the median survey response $\text{MedianScore}_{i,p}$ on the 1 – 5 Likert scale was calculated. Perception weights were derived separately for barriers and facilitators. For barrier features, weights were computed as:

$$\text{PerceptionWeight} = \frac{\text{MedianScore}_{i,p}}{\sum \text{MedianScore}_p} \tag{5.1}$$

Facilitators were assigned weights of the same magnitude but with a negative sign, reflecting their reducing effect on the ImpedanceScore. Because only a small number of facilitators were identified, normalising them independently would have disproportionately overestimated their influence. Assigning them mirrored, negative weights ensures that facilitators with the same median severity as barriers exert a comparable but opposite effect.

Combining the objective severity of microscale street elements captured by the ElementScores with the user-specific importance reflected in the PerceptionWeights, an ImpedanceScoreRaw (Equation 5.2) was calculated for each population group and for each segment of the pedestrian network as a weighted sum of the two components:

$$\text{ImpedanceScoreRaw} = \sum_{i=1}^{n} (\text{ElementScore}_i \times |\text{PerceptionWeight}_i|) \tag{5.2}$$

The resulting ImpedanceScoreRaw was subsequently normalised (Equation 5.3) to the range [-1, 1], where 0 indicates no net impact on accessibility, positive values indicate that the segment impedes movement, and negative values indicate that the segment facilitates movement:

$$\text{ImpedanceScore} = \begin{cases} 0, & x = 0 \\ \dfrac{x}{\max(x)}, & x > 0 \\ \dfrac{-x}{\min(x)}, & x < 0 \end{cases} \tag{5.3}$$

where x is the raw impedance score.

Table 5.3: Survey-derived PerceptionWeights assigned to each accessibility feature for different population groups. The median column reports the median survey response (on a 1–5 Likert scale) for each feature within each population group.

Accessibility Feature	**Mobility-impaired**		**Visually impaired**	
	Median	**PerceptionWeight**	**Median**	**PerceptionWeight**
Barriers				
Narrow sidewalk	3	0.081	2	0.069
Steep sidewalk	3	0.081	1	0.034
Small Scale Obstacles	3	0.081	3	0.103
Large Scale Obstacles	4	0.108	3	0.103
Steps / Stairs	5	0.135	2	0.069
Surface Material Type	3	0.081	2	0.069
Surface Problem	3	0.081	3	0.103
High Kerbs	4	0.108	2	0.069
Shared Space	2	0.054	3	0.103
No Sidewalk	3	0.081	3	0.103
Unmarked Crosswalk	2	0.054	2	0.069
No Accessible Pedestrian Signal	2	0.054	3	0.103
Facilitators				
Kerb Ramp	5	-0.135	4	-0.138
Crosswalk	4	-0.108	5	-0.172
Accessible Pedestrian Signal	4	-0.108	5	-0.172

In addition to using perception-based weights for accessibility features, we included further constraints to reflect the mobility limitations of each population group. For people with mobility impairments, segments with stairs, missing kerb ramps, impassable obstacles, or areas that are too narrow (i.e., sidewalk width below 1 metre) or too steep (i.e., sidewalk slope above 6%) were considered completely inaccessible and removed from their suitable network. For people with visual impairments, we adjusted the severity levels of certain features to account for their unique navigation challenges. For example, kerb ramps without tactile paving received higher severity levels than those used for mobility-impaired individuals.

Using these group-specific parameters, we created three separate network graphs using the *igraph* (Csardi & Nepusz, 2006) and *sfnetworks* (van der Meer et al., 2024) packages in R version 4.3.2 (R Core Team, 2023): one for mobility-impaired individuals, one for visually impaired individuals, and one network with no accessibility information for unrestricted movement by the general population.

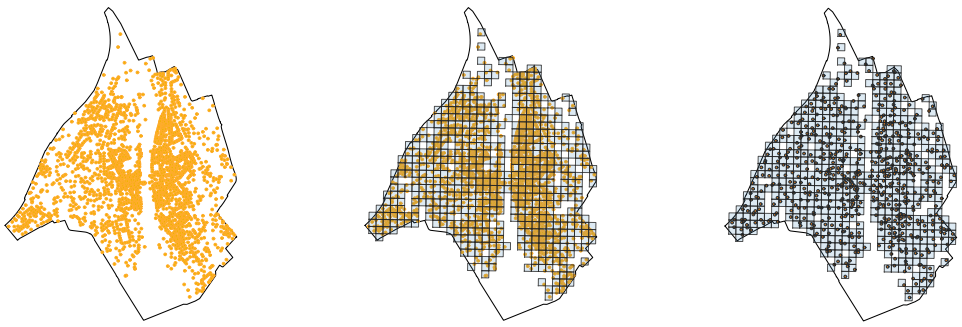
5.3.4.3 Accessibility patterns analysis

Using the graphs, we computed the most accessible routes between address points based on the Segment Cost (Equation 5.2) for each population group, using Dijkstra's algorithm (Dijkstra, 1959). Rather than focusing on a specific facility type, typically represented by a point of interest (POI), we examined accessibility between all the geocoded addresses within the study area. This approach allows us to isolate the effects of infrastructure and individual mobility capacities, minimising the influence of service availability on the analysis. Moreover, individuals may travel for reasons beyond accessing specific facilities, such as visiting friends or family.

The SegmentCost also accounts for segment length to avoid long, unrealistic routes consisting solely of segments with no accessibility features. This approach allowed us to generate the most accessible routes, both efficient in terms of distance and tailored to each group's actual accessibility needs.

$$\text{SegmentCost} = \text{length} \times (1 + \text{ImpedanceScore}) \tag{5.4}$$

Given the high density of address points, over 2,400 in total, many of which were densely clustered, a 50x50 metres grid was overlaid on the study area (Figure 5.5). Within each grid cell (n = 551), a stratified random sampling approach was employed to select 20% of the address points. In cells containing five or fewer address points, a single point was randomly selected to ensure comprehensive spatial coverage. To uncover general patterns of accessibility across the study area (Section 5.4.2), we calculated, for each grid cell, the median route length from all sampled address points within that cell to every other address point in the study area. For each address point in the cell, we computed the lengths of routes to all other address points and then took the median of all these route lengths. To ensure the robustness of the results, the analysis was repeated using multiple random samples of address points. The outcomes remained largely consistent across these runs, indicating that the findings are not sensitive to the specific sample used.



(a) (b) (c)

Figure 5.5: (a) Distribution of all geocoded addresses; (b) 50x50 metre grid layer superimposed over the address points; (c) distribution of selected address points selected by a stratified random sampling approach.

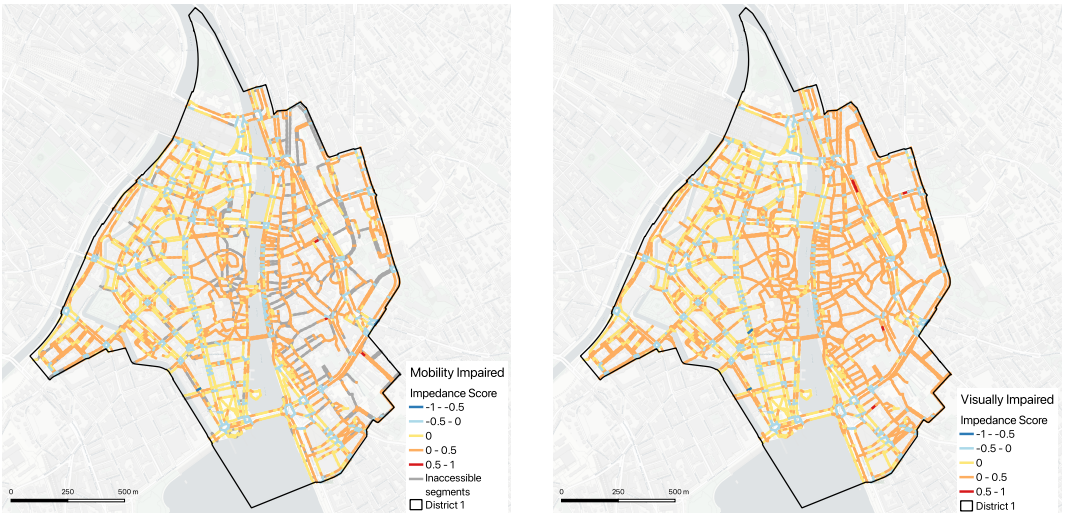
5.3.4.4 Between-groups comparison

To assess how the impact of microscale street elements on spatial accessibility differed across population groups, we conducted a two-level comparison of the generated routes. First, we compared routes based on their length distribution and the frequency with which individual microscale features were observed. Second, to explore route differences in greater detail, we divided the routes into four length categories (0–500 m; 500–1000 m; 1000–1500 m; 1500–2000 m) and selected one example from each category per group for closer examination.

5.4 Results

5.4.1 Impedance score

Figure 5.6 shows the spatial distribution of the impedance score for each 20-metre segment of the pedestrian network for both population groups. The lower the score, the more accessible a segment is, with segments that have a score equal to 0 being fully accessible and segments with a negative score having their accessibility enhanced due to the presence of facilitators.



(a) (b)

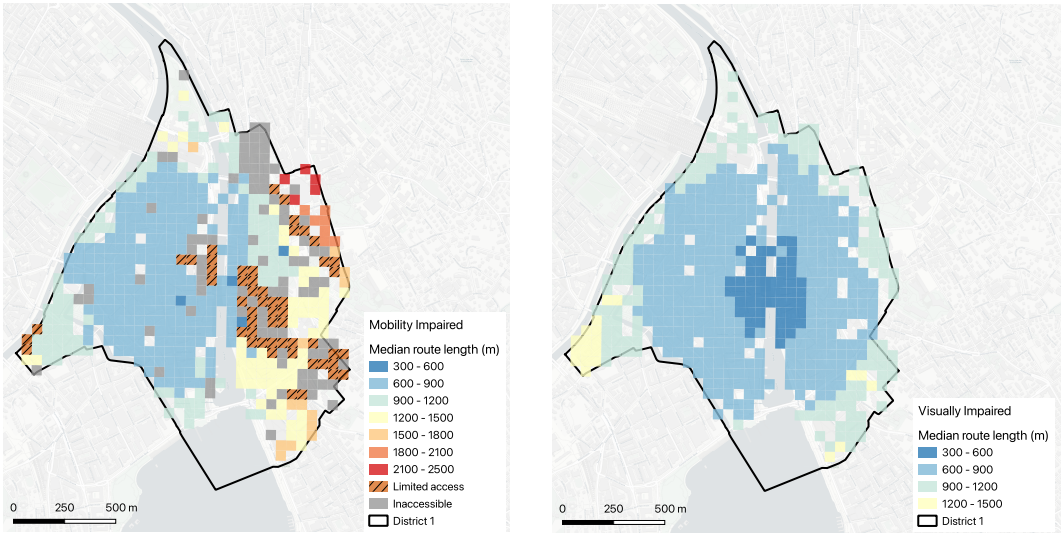
Figure 5.6: The spatial distribution of the impedance score for (a) the mobility-impaired and (b) visually impaired individuals.

In general, for both population groups, less accessible segments are observed in the eastern part of the study area compared to the western part. Approximately 29% of the network segments had an impedance score of 0 for both population groups, indicating full accessibility. These segments are flat, sufficiently wide, and contain no features that either hinder or facilitate accessibility. Roughly 8% of the segments showed enhanced accessibility, with scores below 0. These segments are predominantly located at intersections, consistent with the fact that the only facilitators included in the dataset (kerb ramps, marked crosswalks, and pedestrian signals) are typically located there. Mobility-impaired individuals, however, encounter numerous inaccessible intersection segments, primarily due to high kerbs, which disproportionately affect their ability to navigate the environment. However, the number of high kerbs recorded in the study area was relatively low (n = 43), limiting their overall impact on the results.

The most significant difference between the two population groups emerges when examining segments with an impedance score greater than 0. While nearly two-thirds of the segments (63%) show some level of impediment for both groups, all of these remain at least partially accessible for visually impaired individuals. In contrast, approximately 26% of these segments are classified as completely inaccessible for individuals with mobility impairments. The main reasons for inaccessibility among the mobility-impaired population include slopes exceeding 6%, sidewalks narrower than 1 metre wide, and stairs.

5.4.2 Accessibility patterns

Figure 5.7 shows how microscale street elements influence accessibility patterns for the two population groups, revealing significant differences within the study area. Visually impaired individuals generally have shorter routes across most grid cells, with a gradual, centralised pattern of shorter routes in the centre and longer routes toward the edges. Conversely, mobility-impaired individuals face more movement constraints, especially in the eastern part of the study area, where longer routes and many inaccessible cells are found. Sharp inaccessibility zones often border accessible areas, indicating local barriers blocking the paths.



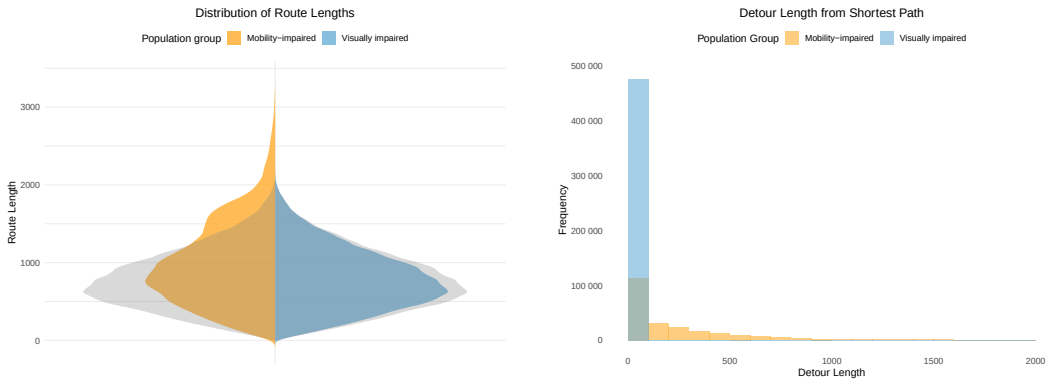
(a) (b)

Figure 5.7: Distribution of median route lengths per grid cell in District 1 for (a) mobility-impaired individuals and (b) visually impaired individuals. Blue shades represent shorter median route lengths, while red shades indicate longer ones. Grey cells correspond to locations where address points have no accessible routes to any other points within the district, indicating complete inaccessibility due to environmental barriers. Orange-hatched cells indicate areas with very limited accessibility, restricted to the respective cell and its neighbouring cells.

Beyond longer routes, mobility-impaired individuals also face significant restrictions in some areas. Approximately 10% of grid cells (hatched cells in Figure 5.7a), the majority of which are in the eastern part of the study area covering the old town, offer limited access, restricted to within the cell or to adjacent cells, meaning that around 13% of address points in the study area are limited to an average travel distance of 60 metres when trying to avoid accessibility barriers. Furthermore, 17% of grid cells (dark grey in Figure 5.7a), concentrated mainly in the eastern part and affecting roughly 14% of address points, are entirely inaccessible due to infrastructure constraints. These hindrances also reduce overall accessibility: on average, a mobility-impaired individual cannot access 20% of the district from any given location, compared to visually impaired individuals. This is also why, in the western part of the study area, we can observe mobility-impaired individuals taking overall shorter routes than the visually impaired, stemming from restricted access to the eastern part.

5.4.3 Between-groups comparison

To further investigate differences between the two population groups and how they compare with the shortest path baseline, we examined route lengths across all three scenarios (Figure 5.8). The distribution of route lengths across the study area for mobility-impaired individuals (Figure 5.8a) is wider and right-skewed, reflecting longer, more variable routes likely driven by accessibility constraints. In contrast, the visually impaired group shows a narrower distribution, although their route lengths still tend to exceed the shortest path baseline.



(a) (b)

Figure 5.8: (a) Violin plot showing the distribution of route lengths for mobility-impaired (orange) and visually impaired (blue) users. The grey distribution represents baseline route lengths for the shortest (distance-minimising) paths without accessibility constraints. (b) Overlaid histograms showing the detour length relative to the shortest-path baseline for mobility-impaired (orange) and visually impaired (blue) individuals.

In Figure 5.8b, similar disparities are highlighted regarding the detours each population group experiences compared to the shortest path. Visually impaired individuals mostly face minor detours, typically under 100 metres. In contrast, mobility-impaired individuals experience significantly longer detours, up to nearly 2000 metres, due to accessibility barriers. These results underscore how infrastructure limitations may impose substantial additional travel distances.

The tendency for accessible routes to avoid barriers is also reflected in the average number of accessibility features per route across the three scenarios (Figure 5.9). Overall, the occurrence of barriers is slightly lower for visually impaired individuals than for the shortest path, and even lower for mobility-impaired individuals. However, some features, such as surface conditions (e.g., uneven or cracked sidewalks) and small-scale obstacles, appear with similar frequency across the shortest paths and the accessible routes generated for both population groups, suggesting they have a limited effect on route accessibility.

In contrast, the presence of facilitators increases for both visually and mobility-impaired individuals, suggesting a preference for intersection segments within their routes. This is further evidenced by the slightly higher frequency of unmarked crosswalks along accessible routes for both population groups compared to the shortest path. Although these are themselves considered barriers, their increased presence may reflect attempts to avoid more

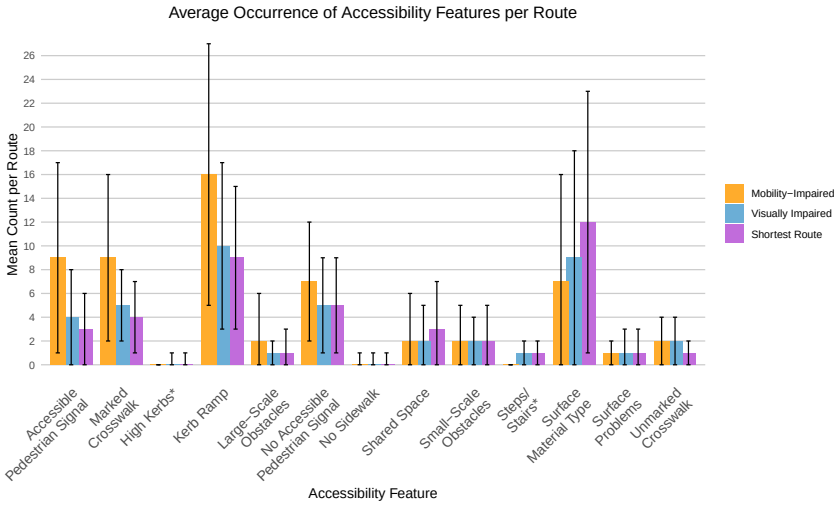


Figure 5.9: The average number of times each accessibility feature was met along the best route, for each of the three scenarios. Only the origin-destination pairs where routes existed for both population groups were taken into consideration. Values are rounded to whole integers. *For mobility-impaired individuals, the number of height differences and high kerbs is zero because the model excludes the corresponding 20-metre network segments based on accessibility requirements. Other zero values result from very few occurrences across all routes, which round down to zero.

restrictive sidewalk obstacles by crossing the street. Interestingly, the frequency of large-scale obstacles is slightly higher among mobility-impaired individuals than among the other groups. However, for both population groups, the variation in the occurrence of these features is high, indicating that the routes generated can vary significantly in terms of accessibility.

Comparing the routes generated for the two population groups, 79.2% end up being longer for mobility-impaired individuals (Figure 5.10). While more than three-quarters of the routes show differences of less than 500m, in some instances the disparity in route length can be substantial, reaching up to 2000 metres. Approximately 17.8% of routes show no difference in length between the two groups. A small number of routes are shorter for mobility-impaired individuals, but these cases are rare, and the differences are minimal, with the largest difference showing the accessible mobility-impaired route is 29 metres shorter than the route generated for visually impaired individuals between the same origin and destination points.

To better understand how microscale street elements contribute to route disparities between the two population groups, we first focused on origin-destination pairs in which the accessible route was longer for mobility-impaired individuals. These 114,115 routes were grouped by length difference: 0–500 metres (85%), 500–1000 metres (11.73%), 1000–1500 metres (2.61%), and 1500–2000 metres (0.66%). For each category, one pair was selected to illustrate how specific accessibility constraints contribute to longer routes for mobility-impaired individuals compared to visually impaired individuals.

In Figure 5.11, we show these four route situations, each with numerical labels denoting selected accessibility features that we describe below. All four examples reflect a broader trend: the accessible routes for mobility-impaired individuals generally follow the study area's main roads, where sidewalks are typically wider. The routes also tend to avoid the

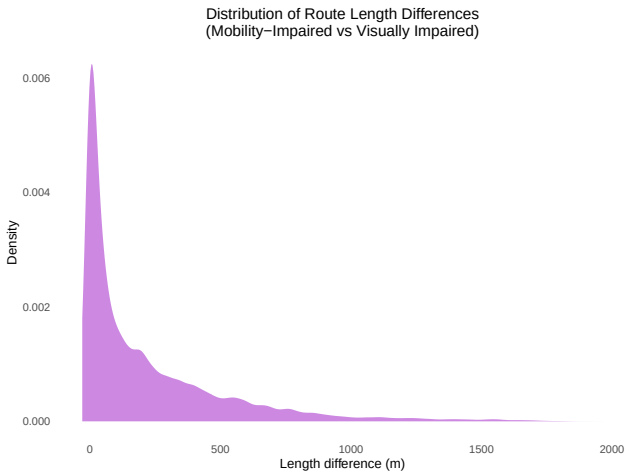


Figure 5.10: The average number of times each accessibility feature was met along the best route, for each of the three scenarios. Only the origin-destination pairs where routes existed for both population groups were taken into consideration. Values are rounded to whole integers. *For mobility-impaired individuals, the number of height differences and high kerbs is zero because the model excludes the corresponding 20-metre network segments based on accessibility requirements. Other zero values result from very few occurrences across all routes, which round down to zero.

old town, where barrier density is higher, and slopes are steeper. In Figure 5.11c, Labels 4 and 5, and Figure 5.11d Label 4, it can be seen how single barriers such as construction sites (Figure 5.11d, Label 4), stairs (Figures 5.11c, Labels 4 and 5), and parked vehicles obstructing the sidewalk (Figure 5.11c, Label 5) contribute to considerable detours as they are considered impassable for mobility-impaired individuals. Along the same lines, Figure 5.11a, Labels 1 and 2, Figure 5.11b, Label 1, and Figure 5.11c, Label 3 show that routes often avoid areas with cobblestone paving, which poses additional challenges for mobility-impaired individuals. Detours are not only caused by features present on the accessible route for visually impaired individuals; in Figure 5.11d, Labels 5, 6 and 7, for instance, the accessible route avoids construction zones and streets without sidewalks. Additionally, the steep slopes concentrated in the central and eastern parts of the study area (Figure 5.12) also contribute to substantial detours for mobility-impaired individuals in all four examples.

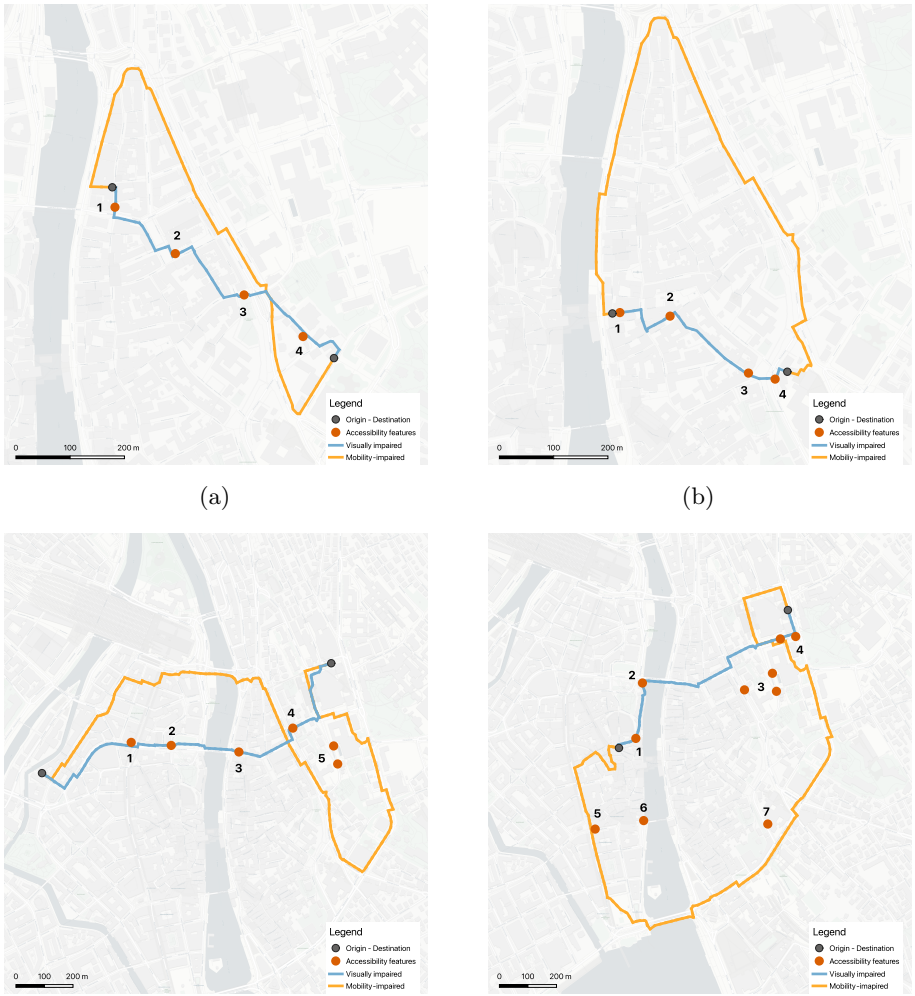


Figure 5.11: Four examples of origin-destination pairs where the accessible route for mobility-impaired individuals (in yellow) is longer compared to visually impaired individuals (in blue). The examples are grouped by route-length difference: 0–500 m, 500–1000 m, 1000–1500 m, and 1500–2000 m. Routes statistics: a) mobility-impaired route length is 1151.3 m and has 20 barriers and 25 facilitators, visually impaired route length is 651.3 m and has 21 barriers and 15 facilitators; b) mobility-impaired route length is 1422.6 m and has 40 barriers and 60 facilitators, visually impaired route length is 424.2 m and has 29 barriers and 7 facilitators; c) mobility-impaired route length is 2916.5 m and has 42 barriers and 79 facilitators, visually impaired route length is 1417.9 m and has 33 barriers and 28 facilitators; d) mobility-impaired route length is 2964.8 m and has 61 barriers and 100 facilitators, visually impaired route length is 999.8 m and has 37 barriers and 22 facilitators.

Instances where the accessible route for mobility-impaired individuals is shorter tend to be concentrated in the western part of District 1. This area is relatively flat (Figure 5.12) and more accessible to mobility-impaired individuals than the rest of the district (Figure 5.7). Two such examples are illustrated in Figure 5.13. In contrast to the examples shown earlier,

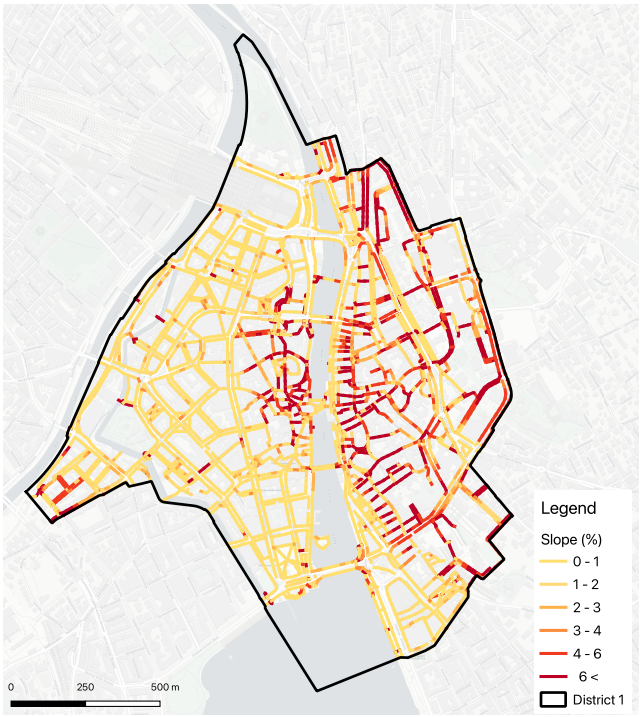


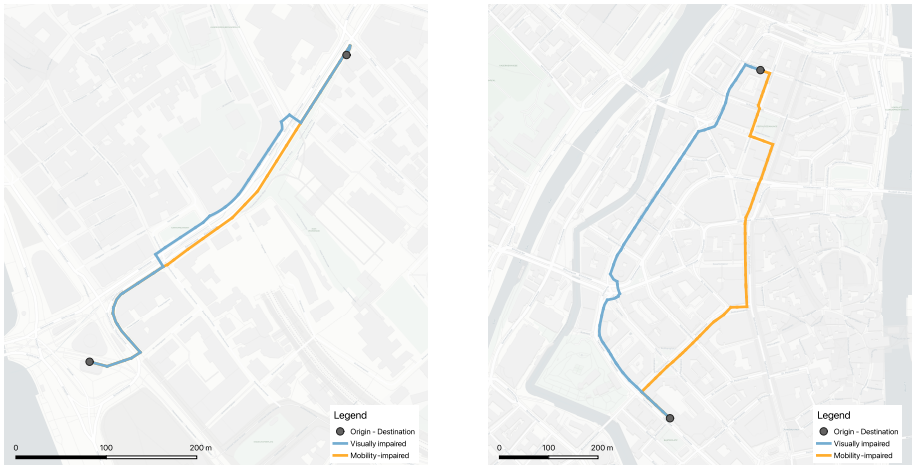
Figure 5.12: Spatial distribution of slope (%) values of 20-metre segments across the pedestrian network in District 1 of the city of Zurich.

in these cases, there is no single microscale street element causing these disparities; rather, the length difference appears to result more from the preferences of the two population groups indicated in the online survey and incorporated into the weighting process. For example, in Figure 5.13, the accessible route for mobility-impaired individuals includes several short segments where space is shared between pedestrians and other modes of transportation. Visually impaired individuals indicated this to be a more severe barrier for their movement than mobility-impaired individuals, and hence, this could be one of the reasons for the difference. However, for cases such as Figure 5.13a, a specific reason for the difference could not be determined.

5.5 Discussion

5.5.1 Pedestrian network enrichment

This study advances accessibility modelling by addressing shortcomings in prior approaches to enriching pedestrian networks with accessibility data. Previous studies often include only a limited set of features (Achuthan et al., 2010; Gharebaghi et al., 2018; Kasemsuppakorn & Karimi, 2009; Šakaja et al., 2019) and treat them as binary, either present or absent (Achuthan et al., 2010; Cepolina & Tyler, 2004). Such simplifications overlook the complexity of urban environments, especially for individuals with diverse mobility needs. Most studies focus on physical barriers, like obstacles or stairs (Achuthan et al., 2010; Šakaja et al., 2019; Tajgardoon & Karimi, 2015; Vale et al., 2017), neglecting facilitators such as kerb ramps,



(a) (b)

Figure 5.13: Two pairs of origin-destination points for which the most accessible route for mobility-impaired individuals is shorter than for visually impaired individuals. Routes statistics: a) mobility-impaired route length is 370 m and has 20 barriers and 14 facilitators, visually impaired route length is 399.4 m and has 9 barriers and 36 facilitators; b) mobility-impaired route length is 900 m and has 14 barriers and 20 facilitators, visually impaired route length is 919 m and has 16 barriers and 32 facilitators.

pedestrian signals, and tactile paving that can improve accessibility. Our approach overcomes these limitations by enriching the pedestrian network with a comprehensive and fine-grained set of features, assigning severity levels to both barriers and facilitators to indicate their impact on movement. This allows the model to capture not just the presence of features but their relative impact on accessibility within the local context.

All accessibility data were integrated into the network as point features, regardless of whether they represented discrete (e.g., benches, poles) or continuous elements (e.g., surface material type). This point-based method is consistent with approaches used in previous accessibility research (Achuthan et al., 2010; Sobek & Miller, 2006). In contrast, Beale et al. (2006) incorporated discrete features alongside segment-level attributes, such as surface type, allowing for a more accurate representation of continuous features. Although our dataset originated as point features, each point was subsequently assigned to a corresponding network segment, which enabled the modelling of segment-level characteristics, such as the presence of particular surface types or inclusion within pedestrian zones, along the network. While this process may introduce minor positional inaccuracies, the use of short segment lengths (maximum 20m) helps to minimise their impact.

To enhance the representation of accessibility features, clustering was applied to aggregate features recorded multiple times, preventing overrepresentation of certain segment characteristics. GDBSCAN was advantageous as it incorporated non-spatial attributes, such as the user who collected the features and their category (e.g., kerb ramp, obstacle, crosswalk). This was crucial for removing user-level duplicates and ensuring distinct feature types were not incorrectly grouped. However, parameter selection, particularly the maximum distance

between clustered features (eps), required careful calibration. Since spatial distribution varies by category, kerb ramps are closely spaced, while outdoor dining areas or stairs are more dispersed, parameters needed category-specific calibration. Due to the sensitivity of the parameter settings, some features might still be duplicated, potentially influencing analysis, while others might have been incorrectly clustered, underestimating microscale elements. While this points to a trade-off between automation and manual editing, interactive post-hoc quality control uncovered few errors overall, meaning that our automated workflow is a feasible approach.

5.5.2 Impedance score

Our results showed greater variability in segment accessibility among mobility-impaired individuals than among visually impaired individuals, with the former exhibiting more segments with low or no accessibility. These findings align with existing literature, such as Tajgardoon and Karimi (2015), where mobility-impaired individuals also experienced more uncomfortable and inaccessible segments when compared to visually impaired individuals. Our analysis extends these insights by incorporating detailed accessibility data and calibrating feature influence using real-world perception data from affected populations, rather than relying solely on literature-based weightings.

When analysing the spatial distribution of impedance scores (Figure 5.6), intersection segments exhibited negative (facilitating) scores, while sidewalk segments tended to have positive (impeding) scores. These results contradict earlier studies that found intersection segments challenging for mobility-impaired individuals (Šakaja et al., 2019). This discrepancy can be explained by several reasons. First, sidewalk infrastructure is highly variable and can differ greatly between countries and cities. Second, most studies in this domain do not consider the positive impact of facilitators and focus mainly on barriers. Last, our findings may partly be due to the dataset including a limited set of facilitators, primarily related to intersections (e.g., kerb ramps, accessibility signals, zebra crossings), with no facilitators along sidewalks (e.g., benches, lighting, ramps). Although some intersection elements may pose barriers (e.g., broken or steep kerb ramps, tram tracks), their presence was broadly interpreted as positive to differentiate from their absence. Moreover, because the dataset was primarily designed to identify barriers rather than the full spectrum of accessibility features, facilitators beyond intersections were largely absent. To develop a more nuanced understanding, future work should include a broader range of facilitating features, especially along sidewalks, and refine the modelling to better distinguish facilitators from barriers.

5.5.3 Accessibility patterns

Assessing the pedestrian accessibility of the two population groups, based on the enriched pedestrian network, highlights the same story: mobility-impaired individuals experience lower accessibility than visually impaired individuals across most of the study area (Figure 5.7).

Both population groups exhibit higher accessibility levels in the central areas of the district, with accessibility decreasing toward the outskirts. This pattern is partially influenced by the edge effect, which results from delimiting the analysis to the boundaries of the study area, thereby excluding destinations or possible connections beyond the district's edges. While this

boundary effect is important to acknowledge, the primary focus of this study is to compare accessibility differences between the two population groups within the defined study area and to assess how accessible it is for individuals to travel from one location to another within District 1. Since the study area boundaries are identical for both population groups, no bias arises regarding the aims of this study.

A notable observation is that some regions remain inaccessible to individuals with mobility impairments due to unsuitable segments, thereby fragmenting the pedestrian network. A similar pattern of results was also reported by Vale et al. (2017) in their study of pedestrian accessibility for wheelchair users, who identified areas that are entirely inaccessible due to sidewalk obstructions. It is important to recognise that the population profiles considered in our study, particularly those of individuals with mobility impairments, can be understood as representing the "worst-case scenario", meaning we consider segments with certain characteristics, such as stairs, missing kerb ramps, or steep slopes, as completely inaccessible.

When assessing accessibility patterns, although the impedance function accounted for the relative importance of different microscale street elements, it used a compensatory approach, in which facilitators or less-impeding features offset the impact of more significant barriers when calculating segment accessibility. However, both existing studies (Vale et al., 2017) and our empirical data show that this is not always the case, depending on mobility capacity. In some contexts, features such as stairs, narrow sidewalks, or steep gradients may be critical barriers and considered non-negotiable for specific groups. Therefore, we adopted a combined approach that uses the compensatory method only if segments do not include any non-negotiable elements (e.g., stairs and high kerbs in our model for mobility-impaired individuals). Although this approach was used in walkability studies that considered factors such as safety and aesthetics rather than just accessibility, Chan et al. (2021) demonstrated its effectiveness in identifying differences based on individuals' needs and preferences. Consequently, accessibility patterns can vary significantly depending on how non-negotiable street elements are modelled.

5.5.4 Between-groups comparison

The impact of the non-negotiable elements for mobility-impaired individuals is also evident when comparing the length differences between accessible routes for the two groups (Figure 5.8). More than three-quarters of the routes are longer for mobility-impaired individuals, with the most significant difference nearing 2 kilometres in a study area of approximately 1.3 km by 2 km. This is mainly due to obstacle avoidance. As shown in Figure 5.11d, depicting the most extreme detour, the accessible route for mobility-impaired individuals must avoid barriers not only along the visually impaired route but also adjacent ones, making a shorter detour impossible. Further, additional factors that contribute to route length differences include the different weights assigned to accessibility features by the two groups. While less apparent when mobility-impaired routes are longer, this difference is clearer when the visually impaired route is longer. For example, in Figure 5.13b, no obvious barrier or facilitator explains the length difference. However, the mobility-impaired route crosses several short segments where pedestrians share the space with vehicles, which was rated more negatively by visually impaired individuals in our survey than by mobility-impaired ones.

An interesting finding emerged when calculating the average number of times each accessibility feature appears along a route across the three scenarios: while accessible routes generally encounter fewer barriers and more facilitators than the shortest path, mobility-impaired routes showed more large-scale obstacles than both visually impaired routes and the baseline. This is likely due to the 'local' severity level assigned to accessibility features, which is taken into account in the impedance score (Equation 5.2) and segment cost (Equation 5.4). This severity level was different from the 'global' perception that individuals pertaining to the two groups reported in the survey and represents the permeability of the element, given the context that it is located in (Allahbakhshi & Ardüser, 2024). When building population profiles, segments with features rated severity 5 (completely impassable) were excluded for mobility-impaired users. Therefore, any large-scale obstacle that appeared along accessible routes for this population group had lower severity levels. This shows that despite being generally seen as an impeding barrier, some features in this category remain passable depending on their local context. For example, outdoor dining areas are often seen as obstacles, but the amount of clear sidewalk space they leave can differ greatly between locations. This means that even within the same category, features can differ in terms of how permeable they are. However, as Figure 5.9 shows, the average number of elements per route varies widely, making this metric less reliable and reflecting an uneven spatial distribution across the network.

5.5.5 Limitations

While the findings of this study offer valuable insights into how contextual factors shape spatial accessibility for different population groups, several limitations should be acknowledged. First, the individual perceptions used in this study are limited to the relatively small group of participants included in our empirical survey, which constrains the generalisability of the results. However, our sample size is consistent with existing literature focusing on hard-to-reach populations such as individuals with mobility or visual impairments (Cushley et al., 2022; Jenkins et al., 2015; Park & Chowdhury, 2018). Moreover, as demonstrated by our own research experience, collecting such data is highly resource-intensive. This practical constraint partly explains why much of the existing literature in this domain relies on relatively small samples. Due to differences in the samples, other studies might prioritise microscale street elements differently, potentially leading to alternative interpretations of their impact on accessibility. However, most of our findings are either explainable by the methodological framework or align with previous research, suggesting limited variability and a high degree of robustness. Furthermore, most respondents with mobility impairments in our survey were wheelchair users, meaning that the survey data primarily capture their perspective.

Second, we modelled spatial accessibility in terms of distance rather than travel time, due to the lack of reliable data on walking or wheeling speeds for the target population groups. This is particularly relevant for visually impaired individuals, for whom travel time may offer a more representative measure of accessibility. However, the results of this study still provide important insights into how contextual factors impact spatial accessibility differently for our two population groups in terms of distance travelled and what triggers these differences.

Further, our analysis considered routes between all addresses in the study area, without accounting for the maximum walking distance that individuals would travel. Incorporating

population-specific walking distance thresholds could provide a more realistic representation of accessibility patterns. However, our approach allowed us to capture the overall accessibility structure of the pedestrian network, independent of trip purpose or distance preference.

Last, the list of barriers and facilitators considered in this study is not exhaustive and was constrained by data availability (i.e., the data collected in Allahbakhshi & Ardüser, 2024). Nevertheless, compared to the existing literature, our study incorporated a markedly more comprehensive set of microscale features relevant to both population groups, including detailed information on condition and severity levels.

5.6 Conclusion

Understanding how microscale street elements shape pedestrian accessibility is critical for informing inclusive urban design that accommodates the diverse mobility capacities of all individuals. This study aimed to explore how such elements impact spatial accessibility differently depending on individuals' mobility capacities, focusing on mobility- and visually impaired individuals. By enriching the pedestrian network with detailed, fine-grained accessibility data and real-world, empirical data on the perception of street elements as barriers or facilitators to spatial accessibility, we were able to assess the accessibility of the pedestrian network for each group. This approach further facilitated the identification of areas with limited accessibility and highlighted where the groups are most affected and why.

Our findings highlight that the built environment impacts the spatial accessibility of individuals with varying mobility capacities in different ways, pointing out the limitations of one-size-fits-all approaches to pedestrian infrastructure planning. More specifically, individuals with mobility impairments face more severe accessibility barriers and generally experience lower levels of access than visually impaired individuals. For mobility-impaired individuals, certain accessibility features can fully block entire parts of the pedestrian network, resulting in isolated 'islands of inaccessibility'. Additionally, when considering both the accessibility features and individual preferences, the computed accessible routes for mobility-impaired individuals tend to be significantly longer than those for visually impaired individuals, indicating a greater impact of the pedestrian infrastructure on their accessibility.

Based on the results, the following recommendations can be made:

- Ensure an accessible minimum clear width for the sidewalk, minimising the obstruction by street furniture, outdoor dining areas, signage or parked vehicles.
- Replace or overlay surface material types such as cobblestones or uneven paving with smoother, non-slip materials to improve locomotion.
- Introduce more marked crosswalks in very populated areas and install kerb ramps and tactile paving at all intersections where they are missing. Additionally, ensure that all intersections are equipped with pedestrian signals that provide both visual and auditory cues.
- Introduce signage for temporary obstructions such as construction sites outside their perimeter and ensure the availability of an accessible detour.

Future research should broaden the scope of this analysis to include areas beyond sidewalks and pedestrian areas, such as green spaces, public transportation stops and indoor spaces, such as train station buildings. Additionally, it should incorporate additional population groups, including individuals with age-related mobility restrictions and those with situational mobility challenges, such as caregivers or parents with pushchairs. Including these groups would provide a more comprehensive understanding of how spatial accessibility varies across different population groups. Furthermore, due to within-group variability, such as the assistive device used by individuals with mobility impairments, level of fitness or experience, future research should include larger and more diverse samples to be able to capture and model within-group heterogeneities. Lastly, to better understand the impact of microscale street elements on accessibility, subsequent studies should focus on analysing actual mobility data, such as GPS trajectories. While survey data capture individual perceptions as stated preferences, behaviours inferred from GPS trajectories, such as navigating obstacles previously described as challenging out of necessity, serve as revealed preferences and may differ substantially from the stated ones.

6 Synthesis

6.1 Main findings by research objective

This thesis seeks to offer further insight into how internal and external contextual factors shape pedestrian spatial accessibility in urban areas. To address this aim, four research objectives (ROs) were formulated. They focus on: (RO1) identifying and classifying microscale street elements that influence spatial accessibility, (RO2) examining how these elements are perceived by individuals with different mobility capacities, (RO3) developing a workflow to integrate such information into pedestrian networks and thus into accessibility analyses, and (RO4) modelling how microscale street elements, in combination with individuals' subjective perceptions, shape spatial accessibility patterns across population groups with different mobility capacities. The following subsections bring together the main findings for each objective and highlight how they contribute to a broader understanding of spatial accessibility for inclusive mobility.

6.1.1 Identify microscale street elements influencing spatial accessibility (RO1)

Microscale street elements are increasingly recognised as important determinants of pedestrian accessibility (Klicnik & Dogra, 2019; Lid & Solvang, 2016; Neven & Ectors, 2023), as they directly influence how individuals navigate and experience the urban environment (Horak et al., 2025; Li et al., 2025). However, existing research remains fragmented, and there is currently no comprehensive, structured understanding of microscale street elements that influence accessibility across diverse user groups. To address this gap and respond to the first research objective (Section 1.3.1), a systematic literature review was conducted (Chapter 2), synthesising 20 studies to develop a structured categorisation of microscale street elements influencing spatial accessibility across different population groups. This chapter also laid the foundation for the thesis by identifying key gaps in the study and conceptualising microscale street elements in relation to accessibility.

With regard to the population groups considered in the literature, the findings of this review show that most studies examining individuals' perceptions of microscale street elements focus on a single population group (e.g., Cushley et al., 2022; Koon et al., 2020; Rosenberg et al., 2013), thereby limiting the ability to compare how these elements affect accessibility across groups. Furthermore, the literature tends to focus disproportionately on certain populations, particularly mobility-impaired individuals (especially wheelchair users) and older adults, while other groups—such as visually impaired individuals or those experiencing situational mobility restrictions—remain underrepresented. To address this imbalance, this review, and

consequently this thesis, adopts a broader perspective by considering multiple population groups simultaneously, including mobility-impaired individuals, older adults aged 65 and above, situationally restricted individuals, and visually impaired individuals.

Regarding the types of microscale street elements examined, the reviewed studies commonly focus on sidewalk characteristics (e.g., width and surface conditions such as unevenness), crossing infrastructure (e.g., kerbs and their characteristics, or the presence of accessible pedestrian signals), and additional accessibility features such as shared use with other transport modes (e.g., bicycles or scooters), the availability of benches or resting places, and vertical aspects of the streetscape such as slopes or stairs. However, the inclusion and level of detail of these elements vary considerably between studies, resulting in fragmented and often non-comparable evidence. Moreover, based on how frequently elements were mentioned across studies and population groups, the findings of this review support the conclusion that microscale street elements may have different impacts depending on individuals' mobility capacities. However, as different studies consider different sets of microscale street elements, this further constrains the comparability of findings. Addressing this gap requires studies that examine multiple population groups within a consistent analytical framework, enabling a more systematic comparison of how microscale street elements influence accessibility.

In addition to differences in population groups and street elements considered, methodological approaches in the literature also vary considerably. Most studies rely on relatively small samples, often between 20 and 60 participants, and involve a trade-off between depth and scale. Studies employing in-depth methods, such as sit-down or walk-along interviews, provide rich, context-specific insights but are limited in scope (Ottoni et al., 2016; Prescott et al., 2021; Rosenberg et al., 2013), whereas studies with larger and more diverse samples tend to rely on questionnaire-based approaches (Harris et al., 2015; Wazani et al., 2021). These methodological differences influence not only the scale of the studies but also the diversity of street elements identified, with larger surveys typically reporting a broader range of elements, while qualitative approaches provide more detailed insights into how these elements are experienced in context.

Furthermore, the synthesis of these studies reveals several distinct patterns of how microscale street elements influence accessibility. While some elements are consistently perceived as barriers or facilitators across population groups, others are group-specific. For instance, benches, wide sidewalks, and good sidewalk conditions were among the most frequently cited facilitators across multiple studies, with benches being particularly important for older adults due to their role in enabling rest and extending walking range. Similarly, adequate lighting and clearly marked crosswalks were broadly perceived as facilitating safe navigation across groups. In contrast, elements such as accessible pedestrian signals, tactile paving, and auditory or textured cues were primarily relevant for visually impaired individuals, highlighting the importance of sensory information for navigation.

In addition, certain elements exhibit a twofold effect, acting as barriers for some groups while facilitating movement for others. For example, high kerbs, while acting as an important orientation cue for visually impaired individuals, represent a major physical barrier for wheelchair users and other mobility-impaired individuals. Similarly, tactile paving, designed to support navigation for visually impaired individuals, can be perceived as uncomfortable

or obstructive for wheelchair users. These findings highlight fundamental trade-offs in accessibility design, where improving conditions for one group may inadvertently reduce accessibility for another.

Overall, these findings indicate that spatial accessibility is not an intrinsic property of the built environment. Rather, it emerges from the interaction between microscale street elements and individual mobility capacities. Thus, these findings suggest that identical microscale street elements can be perceived and navigated in fundamentally different ways, leading to varying accessibility patterns and behaviours across population groups. The findings further suggest that this variability extends within population groups, where individuals with similar characteristics may experience the same element differently depending on their mobility capacities. These insights highlight the importance of more explicitly accounting for both between-group and within-group variability when examining accessibility, an aspect that remains insufficiently addressed in existing research and is further explored in this thesis.

Contributions. The work presented in Chapter 2 contributes to accessibility research by developing a comprehensive and structured classification of microscale street elements that can be applied across multiple population groups. Consolidating fragmented evidence into a coherent and up-to-date framework provides a common reference that enables researchers and practitioners to systematically identify, compare, and assess the role of microscale street elements in shaping accessibility. This chapter also laid the foundation for the empirical study reported in Chapter 3, allowing for the development of a consistent analytical framework to examine multiple population groups and their perceptions regarding how microscale street elements influence accessibility.

6.1.2 Assess perceived impacts of microscale street elements (RO2)

Although existing studies identify which microscale street elements influence accessibility for different population groups, they often fail to assess how the magnitude of these impacts varies across individual characteristics and spatial contexts (Wazani et al., 2021). Even when elements are classified as barriers, such as cobblestone or uneven sidewalk surfaces, their effects are not uniform. Rather, they exhibit varying degrees of severity depending on individual mobility capacities. For instance, a wheelchair user may still traverse such surfaces, but the level of difficulty and, thus, the impact on accessibility may differ depending on factors such as physical capacities or the type of wheelchair used (e.g., manual versus powered). This highlights that microscale street elements do not function as absolute barriers or facilitators, but rather influence accessibility to varying degrees (Baris & Uslu, 2009; Harris et al., 2015). However, existing studies rarely account for this variation. Instead, they rely on binary classifications that overlook differences in the intensity with which elements are experienced across individuals and contexts. Thus, to address this, an online survey (Chapter 3) was conducted to assess and compare perceived severity and facilitation levels of microscale street elements among individuals with varying mobility capacities, thereby addressing the second research objective (Section 1.3.2).

Consistent with the patterns identified in Chapter 2, the results of Chapter 3 indicate that perceptions of microscale street elements differ significantly across population groups for almost all elements considered. However, these differences are less about whether

elements are perceived as barriers or facilitators, and more about how strongly they affect spatial accessibility. Although most elements are consistently classified similarly as barriers across groups, their impact varies substantially, with some groups experiencing them as considerably more restrictive than others. Differences are particularly pronounced between mobility-impaired and visually impaired individuals, with the former consistently reporting stronger impacts compared to both visually impaired individuals and all other groups. Thus, individuals with mobility impairments are more strongly constrained by microscale street elements. As a result, they experience less access than other groups. However, this pattern may also be influenced by the sample composition, as the majority of mobility-impaired participants in this study were wheelchair users. Differences between the remaining population groups were comparatively smaller.

Although differences between population groups represent the primary source of variation in the perceived impact of microscale street elements on spatial accessibility, the results also indicate additional heterogeneity within groups. Factors such as age, gender, and assistive device use influenced how microscale street elements were perceived, but these effects were less pronounced than those associated with mobility capacities, indicating that between-group differences remain the dominant driver of variation. This suggests that accessibility is largely shaped by differences between population groups but cannot be assumed to be uniform within them, stressing the need for models that account for both between- and within-group variations.

A key pattern emerging from the results is the asymmetric role of barriers and facilitators in shaping accessibility perceptions. Differences between population groups were considerably more pronounced for barriers than for facilitators, indicating that barriers contribute more strongly to perceived accessibility disparities. In contrast, many facilitators were evaluated relatively consistently across groups, suggesting that they are often understood as baseline conditions required for movement (e.g., wide, smooth sidewalks), rather than as features that differentiate accessibility experiences. This asymmetry highlights that accessibility inequalities are more strongly driven by the presence and severity of barriers than by variation in facilitating features. At the same time, this distinction should not be interpreted as separating barriers and facilitators in practice, as improving accessibility often involves addressing both simultaneously (e.g., removing a barrier through the introduction of a facilitating feature). Rather, the findings point to an uneven contribution of different microscale street elements to perceived accessibility differences across population groups.

The twofold effect of microscale street elements identified in Chapter 2 was only partially supported by the findings of Chapter 3. While some differences in how elements function as barriers or facilitators across population groups were still observable, these effects were less pronounced than seen in Chapter 2. For example, lowered kerbs were perceived differently by visually impaired individuals compared to other groups, with a substantial proportion of visually impaired participants rating them as neutral or not facilitating. However, these differences were relatively moderate, and no other elements exhibited similarly strong opposing effects across groups. This discrepancy may be influenced by differences in data collection approaches. In the study reported in Chapter 3, participants evaluated a predefined set of microscale street elements in terms of their severity or facilitating effect. This ensured comparability across respondents, but constrained the range of responses. In contrast, the

studies included in Chapter 2 relied on more open-ended methods, in which participants independently identified relevant microscale street elements and described their impacts. While such alternative approaches may highlight more contrasting experiences, the results of Chapter 3 do indeed suggest that perceptions are not uniformly shared within population groups.

In particular, the variation observed among visually impaired individuals indicates that some perceive lowered kerbs as facilitating, and others experience them as neutral or less relevant, underlining the heterogeneity of accessibility experiences within this group. This variation likely reflects differences in how individuals interact with the built environment, shaped by factors such as the level and type of visual impairment, the use of assistive devices, and individual mobility strategies. For example, high kerbs can serve as important tactile boundaries for individuals using a white cane, allowing them to detect the transition between sidewalk and roadway and thus maintain spatial orientation and safety. At the same time, these kerbs introduce a vertical discontinuity that requires stepping up or down, which may interrupt the flow of movement and increase physical effort or uncertainty, particularly in unfamiliar environments. For individuals who rely more on low vision or use alternative mobility aids, such as guide dogs, kerbs may play a less central role in orientation and instead be experienced as minor obstacles or simply as neutral features that neither significantly facilitate nor hinder movement. These differences suggest that the perceived role of microscale street elements is shaped not only by their physical characteristics but also by the specific role they serve in an individual's navigation strategy. As a result, the same feature can be simultaneously relevant to orientation while also constraining movement, illustrating that its perceived impact arises from the interaction between environmental characteristics and individual mobility capacities rather than from the feature itself.

Furthermore, differences in how microscale street elements are perceived across population groups translate directly into differences in computed spatial accessibility patterns (Chapter 5). Incorporating perception-based weights into accessibility analyses reveals variations in accessible paths that are not captured by models relying solely on network attributes. Thus, these findings highlight the limitations of studies that treat spatial accessibility as a fixed or binary condition, rather than considering the impact of microscale street elements as varying in degree, and that fail to account for how these impacts differ systematically across population groups with varying mobility capacities. As a result, such approaches risk misrepresenting and overestimating spatial accessibility.

Contributions. The work of Chapter 3 contributes to accessibility research by conceptualising the impact of microscale street elements as a matter of degree rather than a binary condition. By systematically quantifying perceived severity and facilitation across multiple population groups, it enables a more differentiated understanding of accessibility that captures both between-group differences and within-group variation. At an unprecedented level of detail and breadth, the results provide a comprehensive empirical assessment of how individuals with different mobility restrictions perceive microscale street elements. Furthermore, the results of this chapter provide a solid empirical basis for the computational accessibility modelling approaches developed in Chapters 4 and 5.

6.1.3 Enrich pedestrian networks with microscale street elements (RO3)

Previous studies have integrated accessibility-related features into pedestrian networks, providing important insights into how microscale street elements influence movement (D'Orso & Migliore, 2020; Hwang, 2022; Vale et al., 2017; Völkel & Weber, 2008). However, these approaches often operate at a level of detail that captures overall accessibility conditions without explicitly linking them to the specific microscale street elements that shape them. For example, some approaches represent accessibility by deriving indicators such as effective sidewalk width, where obstructions such as street furniture are subtracted from the total available space (Vale et al., 2017). Others rely on user-based ratings to classify the overall accessibility of network segments (Völkel & Weber, 2008). Thus, to enable accessibility analyses to include microscale street elements and account for how they impact accessibility differently for individuals with varying mobility capacities, a workflow to enrich pedestrian network-based representations with such information was developed in response to the third research objective (Section 1.3.3). In contrast to the current literature, the proposed approach introduced in Chapter 4 provides a structured way to integrate detailed accessibility-related data, such as the location and characteristics of microscale street elements, into pedestrian networks. These data are linked to individual segments (i.e., 20 m segments created by subdividing the original network), allowing for a more detailed representation of the built environment than is typically captured in conventional pedestrian network models.

While the proposed approach shares similarities with existing methods in how microscale street elements are represented, typically as point-based features, and how these are mapped to corresponding segments of the pedestrian network (Achuthan et al., 2010; Kasemsuppakorn & Karimi, 2008; Sobek & Miller, 2006), it extends these approaches in several important ways. First, the network is segmented into uniform 20 m segments prior to assigning microscale street elements, enabling accessibility conditions to be represented at a much finer spatial resolution, rather than being averaged over longer network segments. More importantly, the proposed approach moves beyond treating microscale street elements as binary attributes associated with network segments (Beale et al., 2006). Instead, it incorporates information on the severity of each element, capturing the extent to which it affects accessibility. This allows the impact of microscale street elements to be represented as varying in degree rather than a simple binary encoding (present or absent), enabling a more nuanced representation of how they influence accessibility.

Furthermore, this enriched representation enables the network to be adapted to different mobility needs and to simulate accessibility accordingly through the use of individual-specific profiles. By incorporating perception-based weights derived in Chapter 3, the workflow can translate differences in perceived severity into segment-level impedance. These impedance scores capture the cumulative impact of microscale street elements on movement and combine locally assigned severity values for individual elements with weights that reflect the extent to which different population groups perceive their impact. By integrating both the local characteristics of the built environment and group-specific perceptions, the approach can enable spatial accessibility analyses to capture not only how difficult a segment is to traverse, but also why. As a result, it can allow spatial accessibility to be linked directly to specific microscale street elements and to reflect how their effects vary, thereby revealing, in detail, how these features contribute to uneven accessibility conditions across the urban environment.

Contributions. Building upon a uniquely detailed and rich dataset developed in a related study (i.e., the ZüriACT project; Allahbakhshi & Ardüser, 2024; Allahbakhshi et al., 2026), the workflow presented in Chapter 4 introduces a structured and transferable framework for enriching pedestrian networks with detailed accessibility information and supports applications such as reliable spatial accessibility assessment, personalised routing, and urban planning interventions. By incorporating detailed environmental characteristics, such as the local impact of microscale street elements at the segment level, it enables spatial accessibility to be modelled and assessed at a finer spatial resolution and in a more context-sensitive manner than previous work. This work also provides the foundation for the routing and spatial accessibility analysis presented in Chapter 5.

6.1.4 Model the impact of microscale street elements and individuals' subjective perceptions on accessibility patterns (RO4)

Current spatial accessibility analyses remain limited in their consideration of diverse mobility capacities (Vale et al., 2017), and accessibility disparities across population groups remain largely underexplored. This concerns, in particular, the ability of accessibility models to account for microscale street elements and how their impacts are perceived by different individuals (Jehle et al., 2024; Tajgardoon & Karimi, 2015). To respond to this gap, a computational study was conducted to analyse accessibility disparities arising from individuals' varying mobility capacities, addressing the fourth research objective (Section 1.3.4).

Building on the workflow developed in Chapter 4, and incorporating perception-based weights derived from the empirical study in Chapter 3, we computationally analysed the spatial accessibility in our study area for two population groups, mobility-impaired and visually impaired individuals. The findings of Chapter 5 reveal substantial differences in accessibility between the two groups when accounting for both the location of microscale street elements and their perceived impact. Mobility-impaired individuals consistently exhibited lower levels of spatial accessibility than visually impaired individuals, at both the aggregate and route levels, demonstrating that microscale street elements constrain accessibility unevenly across population groups.

These findings reinforce and extend the results of Chapter 3, where mobility-impaired and visually impaired individuals also exhibited the most pronounced differences in their perceptions of microscale street elements. In particular, mobility-impaired individuals consistently rated elements as more severe, a pattern reflected in the computational accessibility analysis by longer routes and reduced accessibility. This showcases how the differences in perception identified in Chapter 3 translate into measurable disparities in spatial accessibility, demonstrating that variations in how microscale street elements are experienced are reflected in differences in modelled accessibility patterns and movement through the network. Further, these differences extend beyond variations in overall accessibility levels to determining which parts of the network are accessible. In the analysed network representation, for mobility-impaired individuals, certain microscale street elements, such as stairs or steep slopes, act as impassable barriers that fragment the pedestrian network and create *islands of inaccessibility*. This provides empirical evidence that microscale street elements not only can reduce accessibility levels but can also structurally constrain them, with local barriers producing large-scale accessibility inequalities.

However, the identified *islands of inaccessibility* should be interpreted in the light of the assumptions underlying the modelling framework adopted. They emerge from a deterministic accessibility analysis based on a single transport mode (i.e. pedestrian mobility, without accounting for other transport modes such as public transport), fixed thresholds and the modelling assumptions applied to represent the interaction between microscale street elements and individual mobility capacities. Consequently, they represent one plausible accessibility scenario under the median-case condition. Alternative modelling assumptions, such as different mobility settings or probabilistic parametrisations of mobility capacities (Section 6.5), could produce different accessibility patterns and potentially change the spatial distribution of the identified *islands of inaccessibility*.

Furthermore, the results point to two fundamentally different ways in which microscale street elements shape spatial accessibility. On the one hand, some elements impose gradual constraints, increasing travel effort and resulting in longer or more complex, but still passable, routes. On the other hand, certain elements act as absolute constraints, rendering segments entirely inaccessible, leading to network fragmentation. The extent to which accessibility is reduced or structurally constrained depends on both the type of microscale street element and the individual's mobility capacities. While some barriers can be navigated with increased effort, others impose hard constraints that cannot be overcome. This distinction highlights that spatial accessibility is not simply a matter of areas being more or less accessible, but that certain microscale street elements can render entire parts of the network inaccessible.

At the same time, this distinction also raises important considerations for how such effects are represented in modelling approaches. In this thesis, the perceived impact of microscale street elements is translated into segment-level impedance (with 20-meter segments), implicitly assuming that accessibility constraints can be represented along a continuum of increasing cost. However, the presence of absolute barriers suggests that the relationship between perceived impact and movement constraints may not always be continuous or linear, but may instead involve threshold effects. Furthermore, the extent to which perceived impact translates into movement constraints is likely to be context-dependent, shaped by local infrastructure conditions and individual experience. This suggests that the relationship between perceived impact and movement constraints is shaped by both local infrastructure conditions and the characteristics of the sampled population. As a result, perception-based weights may be specific to the study area and sample and should not be assumed to apply directly to other urban contexts. However, the computational modelling methodology used in this thesis is still transferable.

These considerations are addressed, to some extent, by the approach developed in Chapter 4, in which the impact of microscale street elements is represented not only through group-specific importance but also through locally assigned impact. This allows similar elements within the same category to vary in their degree of passability based on local characteristics, meaning that their influence on accessibility cannot be understood solely by their type. Overall, this emphasises the context-dependent nature of microscale street elements and the need to account for both their local impact and differences in their perceived impact across population groups when modelling spatial accessibility.

Contributions. Building on the preceding chapters, this chapter developed a context-aware spatial accessibility modelling framework that combines microscale street elements with empirically derived perception-based weights, thereby integrating both external (environmental) and internal (individual) determinants of accessibility within a unified computational framework. The approach enables the systematic assessment and comparison of accessibility across different population groups, accounting for variations in how urban environments are experienced. Importantly, it supports spatial accessibility analysis at multiple spatial scales, ranging from aggregated assessments across the entire study area to disaggregated, route-level evaluations. Furthermore, the model distinguishes between impassable elements that render segments inaccessible for specific population groups and elements whose effects can be compensated for by other favourable conditions. The proposed computational modelling framework is transferable to other urban contexts beyond our study area, but its performance is influenced by the availability of detailed, fine-grained data on microscale street elements.

6.2 Key insights

This thesis provides a set of *overarching insights* into how contextual factors influence spatial accessibility, which span across all four research chapters. In doing so, it contributes to a more nuanced understanding of accessibility as a context-dependent and individualised phenomenon.

First, there is a clear understanding of how microscale street elements influence spatial accessibility and how their effects can be systematically represented and quantified. Across the four research chapters, these elements were shown to affect accessibility unevenly, both across population groups and across element types. Their role is captured not only by their presence but also by the magnitude and variability of their effects. While some elements exert a strong influence, creating 'islands of inaccessibility' or requiring substantial detours, others have a more limited impact. In particular, findings of Chapter 5 demonstrated the strong impact of impassable barriers on the spatial accessibility of mobility-impaired individuals. Elements such as steep slopes and stairs fragmented the pedestrian network for mobility-impaired individuals, rendering entire areas inaccessible while also making most of the study area inaccessible outside these fragments of the network (Figure 5.7). Thus, depending on individuals' mobility capacity, microscale street elements can restrict available opportunities, which in turn could isolate individuals or affect their overall well-being. These findings reinforce the importance of moving beyond simplified representations of pedestrian networks and accounting for fine-grained built environment elements when analysing accessibility.

Second, the findings demonstrate the fundamental importance of physical accessibility as a prerequisite for all other dimensions of accessibility. Although accessibility is widely recognised as a multidimensional concept, encompassing aspects such as availability, affordability, and acceptability (Penchansky & Thomas, 1981), the ability to physically reach destinations through the built environment is a fundamental prerequisite for all other dimensions (Gharebaghi et al., 2021). The findings of this thesis demonstrate that when this basic condition is not met, other dimensions of accessibility become secondary. This reinforces the critical importance of ensuring physically accessible pedestrian environments, particularly for individuals with limited mobility. More broadly, it highlights that addressing accessibility inequalities requires prioritising the removal of physical barriers and recognising how constraints in the built environment can systematically exclude certain groups from participating in everyday activities.

Third, accessibility varies with individuals' mobility capacities. Consistent with the conceptualisation of spatial accessibility (Section 1.2.1), the results show that accessibility is not solely determined by the spatial distribution of opportunities or the structure of the transport network, but is mediated by individual mobility capacities. Furthermore, the same accessibility feature can have fundamentally different implications for different individuals, acting as an impassable barrier for some while remaining passable for others. In some cases, this leads to substantial disparities in access, with certain population groups effectively being excluded from parts of the network while others have full access. Additionally, some elements exhibit twofold effects, facilitating movement for some individuals while constraining it for others, highlighting that accessibility varies depending on both individual characteristics and contextual conditions.

Fourth, accessibility is shaped not only by differences between population groups but also by variability within groups. While between-group differences represent the dominant source of variation, meaningful heterogeneity exists within groups, influenced by factors such as mobility capacities, assistive device use, or age. This aligns with existing studies that emphasise that accessibility is filtered through individual capacities, perceptions, and constraints, and cannot be fully understood without accounting for individual-level differences (Lättman et al., 2016; Lotfi & Koohsari, 2009).

Fifth, these findings have important implications for the concept of universal design, which aims to create environments that are usable by all individuals without the need for adaptation (Story, 1998). While this principle remains a key objective in inclusive urban planning (Müller et al., 2022), the results of this thesis suggest that achieving universally optimal solutions is particularly challenging in practice. The observed twofold effects of microscale street elements, as well as the variability in how they are experienced across and within population groups, indicate that design interventions may not benefit all users equally and may, in some cases, involve trade-offs. Further, these findings point to the need for more context-sensitive and flexible approaches that acknowledge diversity in mobility capacities and seek to balance potentially conflicting accessibility needs.

Taken together, the findings across the four research objectives point to a consistent pattern: spatial accessibility emerges from the interaction between microscale street elements, individual mobility capacities, and their context of use. Across the thesis, these interactions were shown to shape accessibility in varying ways, influencing not only how environments are perceived but also how they are navigated and which parts of the network remain accessible. This integrated perspective highlights that spatial accessibility cannot be understood as a fixed property of the built environment, but rather as an outcome of context-specific and individualised interactions between people and their surroundings.

6.3 Implications for practice

By integrating detailed characteristics of the built environment with individuals' real-world perceptions, the framework developed in this thesis enables a more nuanced assessment of how accessibility is experienced across different population groups. In addition, the approach enables microscale simulation of pedestrian movement, allowing evaluation of the effects of

specific infrastructure changes before implementation. This provides urban planners with a practical means to design, test, and compare targeted interventions in a systematic and evidence-based way.

Building on these capabilities, the findings of this thesis suggest that accessibility policies and design guidelines for pedestrian environments should explicitly account for the heterogeneity of mobility capacities and the context-dependent nature of accessibility. The results highlight that certain microscale street elements can have twofold effects across population groups. For example, high kerbs may constitute barriers for wheelchair users while remaining important cues for visually impaired individuals. Rather than relying primarily on uniform standardised values, accessibility guidelines and their implementation should therefore acknowledge such trade-offs and support context-sensitive design solutions. Measures such as combining lowered kerbs with tactile paving already reflect this approach and can help address conflicting requirements across population groups. Thus, the framework developed in this thesis supports the systematic evaluation of such solutions and enables the identification of locations where tailored interventions are most needed by assessing their impacts across multiple population groups.

Furthermore, the main practical value of the proposed tool lies in its ability to support the development of location-specific, tailor-made interventions. By enabling planners to simulate and compare alternative design scenarios, the framework makes it possible to assess the relative effectiveness of different measures, such as removing barriers, introducing facilitating elements, or redesigning pedestrian infrastructure. This allows interventions to be prioritised based on their expected impact on overall accessibility and for specific population groups. In addition, the framework enables a more systematic prioritisation of interventions by combining information on the severity of microscale barriers with user perceptions. This makes it possible to distinguish between universal barriers, those that negatively affect all individuals regardless of their mobility capacities, and group-specific constraints that primarily impact certain population groups. The results of this thesis indicate that elements such as stairs, missing sidewalks, and large obstacles tend to function as universal barriers and should therefore be addressed as a priority in efforts to improve overall accessibility. In contrast, other elements may require more targeted interventions tailored to specific individual needs. This prioritisation approach provides a concrete basis for translating empirical findings into actionable planning strategies.

At the spatial level, the tool further enables the identification of areas with particularly low accessibility, including so-called *islands of inaccessibility* (Chapter 5), where built environment constraints significantly limit pedestrian movement. By identifying not only where accessibility is low, but also which specific elements are responsible and which population groups are most affected, the framework supports more precise and effective intervention planning. In the case of District 1 in Zurich, the results highlight the old town and pedestrian zones as priority areas for improvement. While the historical and topographical characteristics of these areas may limit the scope for large-scale structural changes, targeted measures can still be implemented. These include reducing sidewalk obstructions caused by street furniture or outdoor dining, improving surface materials by replacing uneven cobblestones with smoother and non-slip alternatives, and enhancing accessibility through complementary measures such as improved public transport options in areas where physical interventions are constrained.

Finally, the findings underline the importance of continuously revisiting and refining accessibility guidelines to reflect the dynamic nature of urban environments and the diverse needs of their users. Participatory approaches that actively involve individuals with diverse mobility capacities in the design and evaluation of accessibility interventions can further enhance the relevance and effectiveness of these interventions (Neven & Ectors, 2023). At the same time, attention must be paid to the implementation of such guidelines, as discrepancies between formal standards and on-the-ground practices may limit their impact. In this context, the simulation framework developed in this thesis can contribute not only to supporting decision-making but also to identifying and quantifying gaps between policy and practice, provided that detailed data on real-world conditions are available. By capturing how accessibility is actually experienced in the built environment, the tool enables a more systematic assessment of whether implemented measures achieve their intended outcomes, thereby supporting more adaptive and accountable urban planning processes.

6.4 Limitations

While this thesis makes important contributions and provides valuable insights, it also has some limitations arising from its overall conceptual and methodological approach. These limitations define the scope of the findings and should be considered when interpreting the results.

First, the thesis relies on categorising individuals into predefined population groups. This is a common approach in accessibility research, where groups such as mobility-impaired, visually impaired, or older adults are often treated as internally homogeneous (Han et al., 2020; Park & Chowdhury, 2018; Wazani et al., 2021). While such classifications are analytically convenient, they risk overlooking important variation in how individuals experience and navigate the built environment. As also shown in this thesis, individuals within the same population group may exhibit distinct accessibility patterns shaped by differences in mobility capacities, and individual characteristics such as assistive device use, age or gender. This limitation is particularly pronounced for groups defined by age or situational conditions, where mobility capacities can vary widely and change over time. For example, older adults with mobility or visual impairments may fit into multiple categories depending on the perspective adopted. Similarly, individuals experiencing situational mobility restrictions were treated as a single group in this thesis, despite encompassing diverse contexts such as caregivers, individuals recovering from injuries, parents travelling with pushchairs, or people carrying heavy or bulky luggage. These situations involve distinct constraints and interactions with the built environment that are not adequately captured when aggregated into a single category. Overall, while appropriate for the scope of this thesis, this suggests that predefined population groups may oversimplify the diversity of individual mobility experiences and fail to capture important within-group variation. Having said this, the assessment methodology used in Chapter 3 and the simulation framework developed and demonstrated in Chapters 4 and 5 could also be used to drive routing and accessibility analyses at the individual or small-group level.

Furthermore, the perceived impact of microscale street elements was represented using one scalar value, the median rating across respondents, for each element. While this allows for a clear and easily interpretable accessibility analysis, it collapses the underlying distribution of individual perceptions into a single representative value and therefore does not capture the

full variability in how the impact is perceived across individuals. However, the methodology presented in this thesis could be extended by using a more probabilistic approach that takes into account the distributional nature of the perceived impact ratings.

Second, the findings of this thesis are context-dependent and therefore not fully transferable to other urban settings. While the results provide important insights into how individuals with different mobility constraints interact with microscale street elements and how these interactions shape accessibility patterns, they are influenced by the specific characteristics of the study area and data used. The empirical analysis focuses on District 1 in the City of Zurich, which is characterised by relatively high-quality infrastructure, a specific urban morphology, and varied topography, including both hilly and flat areas. In addition, accessibility standards and design guidelines differ across cities and countries, meaning that thresholds used to define accessibility (e.g., acceptable sidewalk width or slope) may vary in other contexts. As a result, the accessibility patterns identified in this thesis may manifest differently elsewhere. However, while the empirical findings are context-specific, the methodological framework developed in this thesis is transferable and can be applied to other urban settings, as it provides a systematic way to incorporate microscale street elements and individual mobility capacities into accessibility analyses, provided that local data are used.

Furthermore, part of the analysis relies on perception-based data derived from a survey conducted with participants across Switzerland. While efforts were made to include a sufficiently large and diverse sample to enable robust comparisons between population groups, the results remain sensitive to sample composition. A different sample could lead to variations in the estimated perceptions and, consequently, in the modelled accessibility patterns. At the same time, the general consistency of the findings with existing literature suggests that the observed patterns are not entirely context-specific. Overall, the results are likely to be most transferable to urban areas with similar infrastructural and morphological characteristics.

Third, this thesis adopts a partial representation of spatial accessibility. While it includes a wide range of microscale street elements and considers multiple population groups with different mobility capacities, it focuses primarily on the interaction between physical microscale street elements and individual mobility characteristics. However, spatial accessibility is shaped by a broader set of contextual factors that are not explicitly captured in this framework. These include temporal factors (e.g., time of day or weather conditions), environmental variability (e.g., traffic), the personal experience and knowledge of the environment, and perceptual dimensions beyond physical capabilities, such as perceived safety, comfort, and confidence. Such factors can significantly influence how accessibility is experienced and may lead to accessibility patterns that differ from those identified in this thesis. Nevertheless, the scope of this thesis was limited to the physical interaction between microscale street elements and individual mobility capacities, as these factors can be systematically measured, explicitly represented within computational models, and directly addressed through urban design and planning interventions.

Fourth, spatial accessibility in this thesis is modelled based on perceived rather than experienced or observed behaviour. The analysis relies on individuals' reports of experiencing microscale street elements, rather than on how they actually navigate the environment in practice. While perception-based data provide valuable insights into how environments are

interpreted and evaluated, they may not fully reflect real-world behaviour, which can be shaped by local constraints, adaptation strategies, or situational factors. At the same time, collecting data on experienced accessibility, for example, through GPS tracking or observational methods, presents practical and ethical challenges, including data privacy concerns, participant burden, and difficulty capturing contextual information. As such, focusing on perceived accessibility remains a valuable and feasible approach, while acknowledging its limitations.

Finally, the validation of the proposed accessibility modelling and simulation framework remains limited. While the model is grounded in empirically derived perception-based weights and therefore reflects how individuals report experiencing the built environment, its correspondence with actual movement behaviour is not directly assessed. As a result, it remains unclear to what extent the modelled accessibility patterns translate into real-world navigation and route choice.

6.5 Outlook

Building on the findings and limitations of this thesis, it is possible to outline key directions for future research. These directions aim to advance understanding of spatial accessibility by incorporating a wider range of data sources, population groups, contextual factors, and spatial dimensions, thereby enhancing spatial accessibility analyses and making them more reflective of real-world conditions.

Future research could explore approaches that go beyond predefined population groups by representing individuals using measurable characteristics of their mobility capacities, rather than relying on categorical groupings. Incorporating attributes such as walking speed, level of fitness, duration of mobility restriction, level of visual impairment, or use of assistive devices would allow for a more fine-grained representation of how individuals interact with the built environment. Alternatively, accessibility analyses could be based on individual or semi-individual profiles that combine multiple characteristics (e.g., a manual wheelchair user with high upper-body strength), enabling more flexible modelling of heterogeneous mobility needs. Such approaches would allow spatial accessibility to be conceptualised as a function of individual capabilities rather than group membership, thereby better capturing both between- and within-group variation.

At the same time, further research is needed to better represent variability within population groups. Though Chapter 3 provides initial insights into within-group heterogeneity, the relatively small sample size limits the robustness of these findings. Addressing this limitation could involve designing empirical studies with larger and stratified samples, enabling structured comparisons across subgroups defined by characteristics such as age, gender, type of mobility restriction, or assistive device use. For example, to build a stratified sample of visually impaired individuals, one could first identify relevant subgroups within the population, such as levels of visual impairment (partially sighted, legally blind, totally blind), age ranges, and use of assistive devices (e.g., white cane, guide dog, none). Furthermore, resampling techniques such as bootstrapping or jackknifing could also be used to assess sample size adequacy. By repeatedly resampling from, or systematically omitting, observations within

an existing dataset, these methods make it possible to evaluate at which point saturation is reached, that is, when enough participants have answered their questionnaire such that adding additional participants does not yield further information (Rohrbach et al., 2016). Such an analysis would provide a more concrete basis for determining appropriate sample sizes in future studies employing similar survey-based approaches.

In addition to refining the sample design, variability within population groups could be accounted for at the modelling stage by moving beyond representing perceived element severity and facilitation with a single summary statistic, such as the median, and instead incorporating the full distribution of participant responses. While the median provides a robust representation of the central tendency, it does not capture the variability in how different individuals perceive the same element. Future studies could account for this variability by performing repeated analyses using representative percentile values (e.g., the 5th, 25th, 50th, 75th, and 95th percentiles) or by adopting a Monte Carlo approach in which severity and facilitation values are repeatedly sampled from the observed distributions. This would allow to understand how robust the identified accessibility patterns are to variation in perceived impact and would allow accessibility analyses to better reflect the diversity of individual mobility experiences.

Beyond improving the representation of individuals, further advances can be achieved by expanding the range of contextual factors considered in spatial accessibility analyses. This thesis focused on two main types of contextual factors: internal factors related to individuals' mobility capacities and external factors represented by microscale street elements along sidewalks, at intersections, and in pedestrian areas. These were selected based on both theoretical relevance and data availability, as identified through the literature review in Chapter 2. However, accessibility is shaped by a broader set of factors that remain only partially captured within this framework. In particular, facilitators necessitate greater attention. As indicated in Chapters 3 and 5, as well as in previous studies, facilitators can have a substantial positive impact on spatial accessibility for individuals with different mobility restrictions. Nevertheless, much of the existing literature continues to focus predominantly on barriers. Although this thesis sought to address this imbalance, the facilitators included were largely limited to those associated with intersections, reflecting constraints in data availability for sidewalks and pedestrian areas. Expanding the identification, collection, and integration of data on facilitators across the full pedestrian infrastructure, therefore, represents an important direction for future research.

In addition, many contextual factors are inherently dynamic rather than static. Elements such as pedestrian traffic, parked vehicles (including cars, bicycles, and scooters), and temporary construction sites can vary over time and significantly influence spatial accessibility conditions. Although some of these elements were considered in this thesis, they were treated as static features. Incorporating their temporal variability would allow spatial accessibility analyses to capture fluctuations in accessibility that remain otherwise undetected. Similarly, broader environmental conditions, including weather, seasonality (Clarke et al., 2017; Wennberg et al., 2009; Willberg et al., 2023), and diurnal variations (Jenkins et al., 2015), can substantially shape how individuals experience and navigate urban environments, and should therefore be more systematically integrated into future analyses.

On top of these external factors, spatial accessibility is also influenced by additional internal perceptual factors that shape how individuals engage with urban space, such as perceived safety and security, perceived risk, and individual confidence (Ståhl et al., 2008). For example, perceived safety can affect whether environments are considered accessible in practice. Certain areas or routes may be avoided for safety reasons, even when they are physically accessible. Such perceptions are often context-dependent and can vary with time of day, visibility or lighting (Kimic & Polko, 2022). As a result, accessibility may fluctuate not only due to physical or environmental conditions, but also due to variations in how individuals perceive and evaluate the environment.

Future research should also broaden the spatial scope of accessibility analyses beyond sidewalks, intersections, and pedestrian areas. While these elements form the core of the pedestrian infrastructure, spatial accessibility is also shaped by other urban environments that play a central role in everyday mobility. Urban green spaces, for instance, support physical and mental well-being and foster social interaction (Lee et al., 2015), yet may also present significant barriers due to unsuitable walking surfaces, insufficient seating, narrow or obstructed pathways, or steep slopes (Błaszczyk et al., 2020). Similarly, large public squares and open pedestrian areas pose challenges for orientation and navigation, particularly for visually impaired individuals (Jenkins et al., 2015).

Furthermore, walking is commonly part of multimodal travel, often combined with public transport. This is particularly relevant for individuals with mobility restrictions, who may be unable to cover long distances on foot (Park & Chowdhury, 2018). Incorporating elements related to access to public transport, such as stops and their surrounding conditions, would therefore enable a more realistic representation of how individuals navigate urban environments. In doing so, accessibility analyses could better capture how different components of the transport system interact, and how areas that are difficult to access on foot alone may become reachable when multimodal options are considered.

Beyond supporting accessibility assessments, the modelling framework developed in this thesis also provides a foundation for the development of personalised pedestrian routing applications. By combining fine-grained accessibility information on microscale street elements with individual mobility profiles, route recommendations could be tailored to the specific needs and preferences of different individuals. For example, individuals could specify preferences to avoid particular elements, such as stairs or high kerbs, could define the maximum slope they are able to sustain, or prioritise routes that include facilitators, such as benches or pedestrian signals at crossings. Such applications would represent a valuable extension of the proposed framework, enabling more personalised and inclusive pedestrian navigation.

Finally, a key direction for future research is bridging the gap between perceived and actual mobility behaviour. While this thesis leverages individuals' subjective perceptions and pedestrian network modelling to infer how contextual factors shape spatial accessibility, these approaches are inherently limited because they capture stated rather than observed behaviour. Survey-based data, although valuable, are subject to limitations, including recall bias, limited accuracy, non-response, and respondent burden, particularly when data collection is time-intensive (Jones et al., 2013; Paulhus, Vazire, et al., 2007; Rolstad et al., 2011). Thus, integrating behavioural mobility data presents a promising direction. Data derived from GPS

trajectories collected via smartphones or wearable sensors (Birenboim & Shoval, 2018; Röcke et al., 2023; Xu et al., 2025) can provide detailed insight into actual movement patterns, enabling the identification of contextual factors by linking observed trajectories to specific environmental conditions and microscale street elements encountered along individuals' routes (Lieu & Guhathakurta, 2025). Moreover, such data can shed light on how individuals navigate microscale street elements in practice, revealing adaptive strategies that may not be captured through self-reported perceptions (Zheng et al., 2008). For example, elements perceived as highly restrictive may still be traversed out of necessity, though less frequently or only under specific conditions. However, such sensor-based approaches also raise important challenges. Positioning data of high temporal resolution and high spatial accuracy are required to reliably capture interactions with microscale street elements, while their collection introduces privacy and ethical concerns, particularly for potentially vulnerable populations (Siła-Nowicka et al., 2016). In addition, recruiting sufficiently large and representative samples may be challenging, as participation may be biased toward individuals who are more motivated or confident in their mobility capacities, limiting the representation of more constrained experiences.

At the same time, GPS trajectories alone lack contextual depth, as they capture movement patterns without providing insight into the motivations, perceptions, or experiences that shape them (Ibrahim et al., 2021). Subjective assessments, therefore, remain essential, as they reveal how individuals interpret and evaluate the built environment (Li et al., 2025), which may be influenced not only by mobility capacities but also by factors such as experience, confidence, or perceived safety (Ståhl et al., 2008). Bringing these perspectives together represents a particularly valuable direction for future research. Integrating perception-based data with observed mobility behaviour would enable a more comprehensive understanding of how microscale street elements influence route choice, detours, and the use or avoidance of specific urban areas. It would also provide a basis for validating spatial accessibility models by comparing modelled outcomes with real-world movement patterns, thereby helping to assess how well these models reflect experienced spatial accessibility.

References

Achuthan, K., Titheridge, H., & Mackett, R. L. (2010). Mapping accessibility differences for the whole journey and for socially excluded groups of people. *Journal of Maps*, *6*(1), 220–229. https://doi.org/10.4113/jom.2010.1077

Aldersey, H., Quadir, M. M., Akter, S., Mozumder, R. H., Nazneen, N., & Nuri, R. P. (2018). Barriers and facilitators for wheelchair users in Bangladesh: A participatory action research project. *Disability, CBR & Inclusive Development*, *29*(2), 24. https://doi.org/10.5463/dcid.v29i2.730

Allahbakhshi, H., & Ardüser, A. (2024). Navigation challenges in urban areas for persons with mobility restrictions. *16th International Conference on Spatial Information Theory (COSIT 2024)*. https://doi.org/10.5167/uzh-262963

Allahbakhshi, H., Ardüser, A., & Rüttimann, F. (2026). ZuriACT: Zurich Accessible CiTy–promoting inclusive urban mobility in zurich through digitalization and participatory research. *Journal of Urban Mobility*, *9*, 100241. https://doi.org/10.1016/j.urbmob.2026.100241

Allahbakhshi, H., & Harrafamoughin, A. (2025). Sidewalk width measurement using street view images and spatial data analysis. *33rd Annual GIS Research UK Conference (GISRUK)*. https://doi.org/10.5281/zenodo.15182508

Allahbakhshi, H. (2023). Towards an inclusive urban environment: A participatory approach for collecting spatial accessibility data in Zurich (short paper). *12th International Conference on Geographic Information Science (GIScience 2023)*, 13–1.

Baris, M. E., & Uslu, A. (2009). Accessibility for the disabled people to the built environment in Ankara, Turkey. *African Journal of Agricultural Research*, *4*(9), 801–814.

Batty, M. (2008). The size, scale, and shape of cities. *Science*, *319*(5864), 769–771. https://doi.org/10.1126/science.1151419

Beale, L., Field, K., Briggs, D., Picton, P., & Matthews, H. (2006). Mapping for wheelchair users: Route navigation in urban spaces. *Cartographic Journal*, *43*(1), 68–81. https://doi.org/10.1179/000870406X93517

Bezyak, J. L., Sabella, S. A., & Gattis, R. H. (2017). Public transportation: An investigation of barriers for people with disabilities. *Journal of Disability Policy Studies*, *28*(1), 52–60. https://doi.org/10.1177/1044207317702070

Bhuiya, M. M. R., Hasan, M. M. U., & Jones, S. (2022). Accessibility of movement challenged persons and challenges faced by their escorting family members–a case study of Dhaka, Bangladesh. *Journal of Transport & Health*, *24*, 101323. https://doi.org/10.1016/j.jth.2021.101323

Bhuiya, M. M. R., Hasan, M. M. U., Mohiuddin, H., Anni, A. H., Chen, Z., & Jones, S. (2024). Inequalities within mobility inequalities: A case study of mode specific problems faced by movement challenged persons of Dhaka, Bangladesh. *Journal of Transport Geography*, *114*, 103784. https://doi.org/10.1016/j.jtrangeo.2023.103784

Birenboim, A., & Shoval, N. (2018). Mobility research in the age of the smartphone. *Geographies of mobility*, 41–49. https://doi.org/10.1080/00045608.2015.1100058

Bivina, G. R., Gupta, A., & Parida, M. (2020). Walk accessibility to metro stations: An analysis based on meso- or micro-scale built environment factors. *Sustainable Cities and Society*, *55*, 102047. https://doi.org/10.1016/j.scs.2020.102047

Błaszczyk, M., Suchocka, M., Wojnowska-Heciak, M., & Muszyńska, M. (2020). Quality of urban parks in the perception of city residents with mobility difficulties. *PeerJ*, *8*, e10570. https://doi.org/10.7717/peerj.10570

Bredmose, A., Grangaard, S., Lygum, V. L., & Hansen, A. R. (2023). Mapping the importance of specific physical elements in urban space for blind and visually impaired people. *Journal of Urban Design*, *28*(2), 139–154. https://doi.org/10.1080/13574809.2022.2097862

Cagney, K. A., York Cornwell, E., Goldman, A. W., & Cai, L. (2020). Urban mobility and activity space. *Annual Review of Sociology*, *46*(1), 623–648. https://doi.org/10.1146/annurev-soc-121919-054848

Campisi, T., Ignaccolo, M., Inturri, G., Tesoriere, G., & Torrisi, V. (2021). Evaluation of walkability and mobility requirements of visually impaired people in urban spaces. *Research in Transportation Business & Management*, *40*, 100592. https://doi.org/10.1016/j.rtbm.2020.100592

Cepolina, E. M., & Tyler, N. (2004). Microscopic simulation of pedestrians in accessibility evaluation. *Transportation Planning and Technology*, *27*(3), 145–180. https://doi.org/10.1080/0308106042000228734

Chan, E. T., Schwanen, T., & Banister, D. (2021). Towards a multiple-scenario approach for walkability assessment: An empirical application in Shenzhen, China. *Sustainable Cities and Society*, *71*, 102949. https://doi.org/10.1016/j.scs.2021.102949

Chen, Y.-J., Matsuoka, R. H., & Tsai, K.-C. (2015). Spatial measurement of mobility barriers: Improving the environment of community-dwelling older adults in Taiwan. *Journal of Aging and Physical Activity*, *23*(2), 286–297. https://doi.org/10.1123/japa.2014-0004

Clarke, P., Hirsch, J. A., Melendez, R., Winters, M., Gould, J. S., Ashe, M., Furst, S., & McKay, H. (2017). Snow and rain modify neighbourhood walkability for older adults. *Canadian Journal on aging/la revue canadienne du vieillissement*, *36*(2), 159–169. https://doi.org/10.1017/S071498081700006X

Corazza, M. V., Di Mascio, P., & Moretti, L. (2016). Managing sidewalk pavement maintenance: A case study to increase pedestrian safety. *Journal of Traffic and Transportation Engineering (English Edition)*, *3*(3), 203–214. https://doi.org/10.1016/j.jtte.2016.04.001

Csardi, G., & Nepusz, T. (2006). The igraph software package for complex network research.

Cushley, L. N., Galway, N., Curran, K., & Peto, T. (2022). Navigating the unseen city: Town planners, architects, ophthalmic professionals, and charity opinions on navigating of the built environment with a visual impairment. *International Journal of Environmental Research and Public Health*, *19*(12), 7299. https://doi.org/10.3390/ijerph19127299

De Vos, J., Ettema, D., & El-Geneidy, A. (2025). The (in) ability to travel and reach destinations. *Transport Reviews*, *45*(6), 829–834. https://doi.org/10.1080/01441647.2025.2572256

Dempsey, N., Bramley, G., Power, S., & Brown, C. (2011). The social dimension of sustainable development: Defining urban social sustainability. *Sustainable Development*, *19*, 289–300. https://doi.org/10.1002/sd.417

Desouza, K. C., & Flanery, T. H. (2013). Designing, planning, and managing resilient cities: A conceptual framework. *Cities*, *35*, 89–99. https://doi.org/10.1016/j.cities.2013.06.003

Dijkstra, E. (1959). A note on two problems in connection with graphs. *Numerische Mathematik*, *1*, 101–118.

D'Orso, G., & Migliore, M. (2020). A GIS-based method for evaluating the walkability of a pedestrian environment and prioritised investments. *Journal of Transport Geography*, *82*, 102555. https://doi.org/10.1016/j.jtrangeo.2019.102555

Dunn, O. J. (1964). Multiple comparisons using rank sums. *Technometrics*, *6*(3), 241–252. https://doi.org/10.2307/1266041

Enable Me. (2026). *Insights by EnableMe*. MyHandicap Foundation. Retrieved February 8, 2026, from https://insights.enableme.org/

Evans, J., & Jones, P. (2011). The walking interview: Methodology, mobility and place. *Applied Geography*, *31*(2), 849–858. https://doi.org/10.1016/j.apgeog.2010.09.005

Ewing, R., & Handy, S. (2009). Measuring the unmeasurable: Urban design qualities related to walkability. *Journal of Urban design*, *14*(1), 65–84. https://doi.org/10.1080/13574800802451155

Fasina, S. O., Salisu, U. O., Odufuwa, B. O., & Akanmu, A. (2020). Travel behaviour and mobility challenges of disabled elderly in selected cities of Ogun State, Nigeria. *LOGI – Scientific Journal on Transport and Logistics*, *11*(1), 25–36. https://doi.org/10.2478/logi-2020-0003

Federal Office of Statistics. (2020). *Area with urban character 2020*. Retrieved January 16, 2026, from https://www.bfs.admin.ch/bfs/en.assetdetail.31265076.html

Federal Office of Topography. (2017). *SwissALTI3D*. Retrieved February 2, 2025, from https://opendata.swiss/it/dataset/swissalti3d

Federal Office of Topography (swisstopo). (2017). Swissalti3d [Retrieved from https://opendata.swiss/it/dataset/swissalti3d].

Figueiredo, M., Eloy, S., Marques, S., & Dias, L. (2023). Older people perceptions on the built environment: A scoping review. *Applied Ergonomics*, *108*, 103951. https://doi.org/10.1016/j.apergo.2022.103951

Forsyth, A. (2015). What is a walkable place? The walkability debate in urban design. *Urban design international*, *20*(4), 274–292. https://doi.org/10.1057/udi.2015.22

Gaglione, F., Gargiulo, C., & Zucaro, F. (2022). Where can the elderly walk? A spatial multi-criteria method to increase urban pedestrian accessibility. *Cities*, *127*, 103724. https://doi.org/10.1016/j.cities.2022.103724

Gamache, S., Routhier, F., Morales, E., Vandersmissen, M.-H., & Boucher, N. (2019). Mapping review of accessible pedestrian infrastructures for individuals with physical disabilities. *Disability and Rehabilitation: Assistive Technology*, *14*(4), 410–422. https://doi.org/10.1080/17483107.2018.1449018

Gao, W., & Nagai, Y. (2021). The influence of street microenvironment on the walking activities of older adults. *Social Sciences*, *10*(12), 451. https://doi.org/10.3390/socsci10120451

Georgescu, A. I., Allahbakhshi, H., & Weibel, R. (2024). The impact of microscale street elements on active transport of mobility-restricted individuals: A systematic review. *Journal of Transport & Health*, *38*, 101842. https://doi.org/10.1016/j.jth.2024.101842

Georgescu, A.-I., Allahbakhshi, H., Harrafamoughin, A., & Weibel, R. (2026). Mind the obstacle: Impact of microscale street elements on urban accessibility disparities. *Journal of Urban Mobility*, *9*, 100203. https://doi.org/10.1016/j.urbmob.2026.100203

Georgescu, A.-I., Allahbakhshi, H., & Weibel, R. (2025). Developing enriched pedestrian networks using accessibility features. *AGILE: GIScience Series*, *6*, 23. https://doi.org/10.5194/agile-giss-6-23-2025

Geurs, K. T., & Van Eck, J. R. (2001). Accessibility measures: Review and applications.

Geurs, K. T., & Van Wee, B. (2004). Accessibility evaluation of land-use and transport strategies: Review and research directions. *Journal of Transport Geography*, *12*(2), 127–140. https://doi.org/10.1016/j.jtrangeo.2003.10.005

Gharebaghi, A., Mostafavi, M. A., Edwards, G., & Fougeyrollas, P. (2021). User-specific route planning for people with motor disabilities: A fuzzy approach. *ISPRS International Journal of Geo-Information*, *10*(2), 65. https://doi.org/10.3390/ijgi10020065

Gharebaghi, A., Mostafavi, M. A., Edwards, G., Fougeyrollas, P., Gamache, S., & Grenier, Y. (2018). Integration of the social environment in a mobility ontology for people with motor disabilities. *Disability and Rehabilitation: Assistive Technology*, *13*(6), 540–551. https://doi.org/10.1080/17483107.2017.1344887

Gould, P. R. (1969). Spatial Diffusion, Resource Paper No. 4.

Hägerstrand, T. (1970). What about people in regional science. *Transport Sociology: Social Aspects of Transport Planning*, 143–158.

Hall, C. M., & Ram, Y. (2018). Walk Score® and its potential contribution to the study of active transport and walkability: A critical and systematic review. *Transportation Research Part D: Transport and Environment*, *61*, 310–324. https://doi.org/10.1016/j.trd.2017.12.018

Hammel, J., Magasi, S., Heinemann, A., Gray, D. B., Stark, S., Kisala, P., Carlozzi, N. E., Tulsky, D., Garcia, S. F., & Hahn, E. A. (2015). Environmental barriers and supports to everyday participation: A qualitative insider perspective from people with disabilities. *Archives of Physical Medicine and Rehabilitation*, *96*(4), 578–588. https://doi.org/10.1016/j.apmr.2014.12.008

Han, S. R., Yoon, S., & Cho, S. (2020). Smart accessibility: Design process of integrated geospatial data models to present user-customized universal design information. *Frontiers in Psychology*, *10*, 2951. https://doi.org/10.3389/fpsyg.2019.02951

Hansen, W. G. (1959). How accessibility shapes land use. *Journal of the American Institute of Planners*, *25*(2), 73–76.

Harris, F., Yang, H.-Y., & Sanford, J. (2015). Physical environmental barriers to community mobility in older and younger wheelchair users. *Topics in Geriatric Rehabilitation*, *31*(1), 42–51. https://doi.org/10.1097/TGR.0000000000000043

Henje, C., Stenberg, G., Lundälv, J., & Carlsson, A. (2021). Obstacles and risks in the traffic environment for users of powered wheelchairs in sweden. *Accident Analysis & Prevention*, *159*, 106259. https://doi.org/10.1016/j.aap.2021.106259

Herrmann-Lunecke, M. G., Figueroa-Martínez, C., Parra Huerta, F., & Mora, R. (2022). The disabling city: Older persons walking in central neighbourhoods of Santiago de Chile. *Sustainability*, *14*(17), 11085. https://doi.org/10.3390/su141711085

Hirsch, J. A., Winters, M., Ashe, M. C., Clarke, P. J., & McKay, H. A. (2016). Destinations that older adults experience within their GPS activity spaces: Relation to objectively measured physical activity. *Environment and Behavior*, *48*(1), 55–77. https://doi.org/10.1177/0013916515607312

Horak, J., Kukuliac, P., Koktava, N., Orlikova, L., & Maresova, P. (2025). Impact of street-level barriers on walking accessibility for persons with declining mobility: Comparison of two cities. *Cities*, *166*, 106220. https://doi.org/10.1016/j.cities.2025.106220

Hwang, J. (2022). A factor analysis for identifying people with disabilities' mobility issues in built environments. *Transportation Research Part F: Traffic Psychology and Behaviour*, *88*, 122–131. https://doi.org/10.1016/j.trf.2022.05.016

Ibrahim, A., Zhang, H., Clinch, S., & Harper, S. (2021). From GPS to semantic data: How and why—a framework for enriching smartphone trajectories. *Computing*, *103*(12), 2763–2787. https://doi.org/10.1007/s00607-021-00993-z

infra3D Web-Client. (2025). *infra3D Web-Client*. Retrieved April 9, 2025, from https://www.inovitas.ch/en/technology/infra3d-webclient

iNovitas AG. (2025). *iNovitas AG*. Retrieved April 9, 2025, from https://www.inovitas.ch/

Jehle, U., Larriva, M. T. B., BaghaiePoor, M., & Büttner, B. (2024). How does pedestrian accessibility vary for different people? Development of a perceived user-specific accessibility measure for walking (PAW). *Transportation Research Part A: Policy and Practice*, *189*, 104203. https://doi.org/10.1016/j.tra.2024.104203

Jenkins, G., Yuen, H., & Vogtle, L. (2015). Experience of multisensory environments in public space among people with visual impairment. *International Journal of Environmental Research and Public Health*, *12*(8), 8644–8657. https://doi.org/10.3390/ijerph120808644

Jones, M., & Pebley, A. R. (2014). Redefining neighborhoods using common destinations: Social characteristics of activity spaces and home census tracts compared. *Demography*, *51*(3), 727–752. https://doi.org/10.1007/s13524-014-0283-z

Jones, T. L., Baxter, M., & Khanduja, V. (2013). A quick guide to survey research. *The annals of the royal college of surgeons of England*, *95*(1), 5–7. https://doi.org/10.1308/003588413X13511609956372

Kapsalis, E., Jaeger, N., & Hale, J. (2024). Disabled-by-design: Effects of inaccessible urban public spaces on users of mobility assistive devices–a systematic review. *Disability and Rehabilitation: Assistive Technology*, *19*(3), 604–622. https://doi.org/10.1080/17483107.2022.2111723

Kasemsuppakorn, P., & Karimi, H. A. (2009). Personalised routing for wheelchair navigation. *Journal of Location Based Services*, *3*(1), 24–54. https://doi.org/10.1080/17489720902837936

Kasemsuppakorn, P., Karimi, H. A., Ding, D., & Ojeda, M. A. (2015). Understanding route choices for wheelchair navigation. *Disability and Rehabilitation: Assistive Technology*, *10*(3), 198–210. https://doi.org/10.3109/17483107.2014.898160

Kasemsuppakorn, P., & Karimi, H. A. (2008). Data requirements and a spatial database for personalized wheelchair navigation. *Proceedings of the 2nd international convention on rehabilitation engineering & assistive technology*, 31–34. https://doi.org/10.5555/1983222.1983232

Kaufmann, V. (2002). *Re-thinking mobility: Contemporary sociology* (1st ed.). Ashgate.

Kaufmann, V., Bergman, M. M., & Joye, D. (2004). Motility: Mobility as capital. *International Journal of Urban and Regional Research*, *28*(4), 745–756. https://doi.org/10.1111/j.0309-1317.2004.00549.x

Kim, S., Park, S., & Lee, J. S. (2014). Meso- or micro-scale? Environmental factors influencing pedestrian satisfaction. *Transportation Research Part D*, *30*, 10–20. https://doi.org/10.1016/j.trd.2014.05.005

Kimic, K., & Polko, P. (2022). The use of urban parks by older adults in the context of perceived security. *International Journal of Environmental Research and Public Health*, *19*(7), 4184. https://doi.org/10.3390/ijerph19074184

King, A. C., & Woodroffe, J. (2017). Walking interviews. In *Handbook of Research Methods in Health Social Sciences* (pp. 1–22). Springer. https://doi.org/10.1007/978-981-10-2779-6_28-1

Klicnik, I., & Dogra, S. (2019). Perspectives on active transportation in a mid-sized age-friendly city: "You Stay Home". *International Journal of Environmental Research and Public Health*, *16*(24), 4916. https://doi.org/10.3390/ijerph16244916

Koon, L. M., Remillard, E. T., Mitzner, T. L., & Rogers, W. A. (2020). Aging concerns, challenges, and everyday solution strategies (access) for adults aging with a long-term mobility disability. *Disability and Health Journal*, *13*(4), 100936. https://doi.org/10.1016/j.dhjo.2020.100936

Kruskal, W. H., & Wallis, W. A. (1952). Use of ranks in one-criterion variance analysis. *Journal of the American Statistical Association*, *47*(260), 583–621. https://doi.org/10.1080/01621459.1952.10483441

Lanza, G., Pucci, P., & Carboni, L. (2023). Measuring accessibility by proximity for an inclusive city. *Cities*, *143*, 104581. https://doi.org/10.1016/j.cities.2023.104581

Lättman, K., Friman, M., & Olsson, L. E. (2016). Perceived accessibility of public transport as a potential indicator of social inclusion. *Social Inclusion*, *4*(3), 36–45. https://doi.org/10.17645/si.v4i3.481

Lättman, K., Olsson, L. E., & Friman, M. (2018). A new approach to accessibility–examining perceived accessibility in contrast to objectively measured accessibility in daily travel. *Research in Transportation Economics*, *69*, 501–511. https://doi.org/10.1016/j.retrec.2018.06.002

Lee, A. C. K., Jordan, H. C., & Horsley, J. (2015). Value of urban green spaces in promoting healthy living and wellbeing: Prospects for planning. *Risk Management and Healthcare Policy*, 131–137. https://doi.org/10.2147/RMHP.S61654

Lee, R. J., Sener, I. N., & Jones, S. N. (2017). Understanding the role of equity in active transportation planning in the united states. *Transport Reviews*, *37*(2), 211–226. https://doi.org/10.1080/01441647.2016.1239660

Li, C., Orii, L., Saugstad, M., Mooney, S. J., Eisenberg, Y., Labbé, D., & Froehlich, J. E. (2022). A pilot study of sidewalk equity in seattle using crowdsourced sidewalk assessment data. *arXiv preprint arXiv:2211.11545*.

Li, C., Pang, R. Y., Labbé, D., Eisenberg, Y., Hosseini, M., & Froehlich, J. E. (2025). Accessibility for whom? Perceptions of mobility barriers across disability groups and implications for designing personalized maps. *Proceedings of the 2025 CHI Conference on Human Factors in Computing Systems*, 1–19. https://doi.org/10.1145/3706598.3713421

Lid, I. M., & Solvang, P. K. (2016). (Dis)ability and the experience of accessibility in the urban environment. *Alter*, *10*(2), 181–194. https://doi.org/10.1016/j.alter.2015.11.003

Lieu, S. J., & Guhathakurta, S. (2025). Exploring pedestrian route choice preferences by demographic groups: Analysis of street attributes in chicago. *Transportation Research Part A: Policy and Practice*, *195*, 104437. https://doi.org/10.1016/j.tra.2025.104437

LimeSurvey. (2025). *LimeSurvey* (Version 6.15.5). https://www.limesurvey.org

Litman, T. (2017). Evaluating accessibility for transport planning.

Litman, T. (2003). Measuring transportation. *Traffic, mobility and accessibility. ITE Journal*, *73*(10), 28–32.

Lo, R. H. (2009). Walkability: What is it? *Journal of Urbanism*, *2*(2), 145–166. https://doi.org/10.1080/17549170903092867

Lotfi, S., & Koohsari, M. J. (2009). Analyzing accessibility dimension of urban quality of life: Where urban designers face duality between subjective and objective reading of place. *Social Indicators Research*, *94*(3), 417–435. https://doi.org/10.1007/s11205-009-9438-5

Macdonald, S. J., Deacon, L., Nixon, J., Akintola, A., Gillingham, A., Kent, J., Ellis, G., Mathews, D., Ismail, A., Sullivan, S., et al. (2018). 'The invisible enemy': Disability, loneliness and isolation. *Disability & Society*, *33*(7), 1138–1159. https://doi.org/10.1080/09687599.2018.1476224

Mann, H. B., & Whitney, D. R. (1947). On a test of whether one of two random variables is stochastically larger than the other. *The Annals of Mathematical Statistics*, *18*(1), 50–60. https://doi.org/10.1214/aoms/1177730491

Mao, X., & Chen, L. (2022). "To go, or not to go, that is the question": Perceived inaccessibility among individuals with disabilities in shanghai. *Disability & Society*, *37*(10), 1659–1677. https://doi.org/10.1080/09687599.2021.1899897

Martin, S. A. (2015). A framework to understand the relationship between social factors that reduce resilience in cities: Application to the City of Boston. *International Journal of Disaster Risk Reduction*, *12*, 53–80. https://doi.org/10.1016/j.ijdrr.2014.12.001

Marwal, A., & Silva, E. (2022). Literature review of accessibility measures and models used in land use and transportation planning in last 5 years. *Journal of Geographical Sciences*, *32*(3), 560–584. https://doi.org/10.1007/s11442-022-1961-1

Matthews, H., Beale, L., Picton, P., & Briggs, D. (2003). Modelling access with GIS in urban systems (MAGUS): Capturing the experiences of wheelchair users. *Area*, *35*(1), 34–45. https://doi.org/10.1111/1475-4762.00108

McMullan, K., & Butler, M. (2019). Self-regulation when using a mobility scooter: The experiences of older adults with visual impairments. *British Journal of Occupational Therapy*, *82*(8), 512–521. https://doi.org/10.1177/0308022619853528

Meyers, A. R., Anderson, J. J., Miller, D. R., Shipp, K., & Hoenig, H. (2002). Barriers, facilitators, and access for wheelchair users: Substantive and methodologic lessons from a pilot study of environmental effects. *Social Science & Medicine*, *55*(8), 1435–1446. https://doi.org/10.1016/S0277-9536(01)00269-6

Miller, E. J. (2018). Accessibility: Measurement and application in transportation planning. *Transport Reviews*, *38*(5), 551–555. https://doi.org/10.1080/01441647.2018.1492778

Millstein, R. A., Cain, K. L., Sallis, J. F., Conway, T. L., Geremia, C., Frank, L. D., Chapman, J., Van Dyck, D., Dipzinski, L. R., Kerr, J., Glanz, K., & Saelens, B. E. (2013). Development, scoring, and reliability of the microscale audit of pedestrian streetscapes (maps). *BMC Public Health*, *13*, 403. https://doi.org/10.1186/1471-2458-13-403

Mogaji, E., Bosah, G., & Nguyen, N. P. (2023). Transport and mobility decisions of consumers with disabilities. *Journal of Consumer Behaviour*, *22*(2), 422–438. https://doi.org/10.1002/cb.2089

Mohiuddin, H., Bhuiya, M. M. R., Hasan, M. M. U., & Jamme, H. T. (2024). How individual perceptions of transportation systems influence mode choice for mobility-challenged people. *Transport Policy*, *147*, 259–270. https://doi.org/10.1016/j.tranpol.2023.12.017

Moura, F., Cambra, P., & Gonçalves, A. B. (2017). Measuring walkability for distinct pedestrian groups with a participatory assessment method: A case study in Lisbon. *Landscape and Urban Planning*, *157*, 282–296. https://doi.org/10.1016/j.landurbplan.2016.07.002

Müller, L., Ericsson, S., & Hedvall, P.-O. (2022). Visions of a city for all: Resources, choices and factors supporting and impeding universal design in the urban development process. *The Journal of Public Space*, *7*(2), 63–78. https://doi.org/10.32891/jps.v7i2.1486

Mwaka, C. R., Best, K. L., Cunningham, C., Gagnon, M., & Routhier, F. (2024). Barriers and facilitators of public transport use among people with disabilities: A scoping review. *Frontiers in Rehabilitation Sciences*, *4*, 1336514. https://doi.org/10.3389/fresc.2023.1336514

Naumann, R. B., Dellinger, A. M., Haileyesus, T., & Ryan, G. W. (2011). Older adult pedestrian injuries in the United States: Causes and contributing circumstances. *International Journal of Injury Control and Safety Promotion*, *18*(1), 65–73. https://doi.org/10.1080/17457300.2010.517321

Neutens, T. (2015). Accessibility, equity and health care: Review and research directions for transport geographers. *Journal of Transport Geography*, *43*, 14–27. https://doi.org/10.1016/j.jtrangeo.2014.12.006

Neven, A., & Ectors, W. (2023). "I am dependent on others to get there": Mobility barriers and solutions for societal participation by persons with disabilities. *Travel Behaviour and Society*, *30*, 302–311. https://doi.org/10.1016/j.tbs.2022.10.009

Núñez, F., Albornoz, E., León, J., & Zumelzu, A. (2022). Socially sustainable mobility: Strategic analysis to identify accessibility barriers. *Sustainable Cities and Society*, *76*, 103420. https://doi.org/10.1016/j.scs.2021.103420

Open Data Zürich. (2021). *Amtliche Vermessung - Datenmodell ZH (Standard) (OGD) (kantonaler Datensatz)*. Retrieved February 3, 2025, from https://www.stadtzuerich.ch/geodaten/download/10016?format=128

Open Data Zürich. (2022). *Fuss- und Velowegnetz*. Retrieved February 2, 2025, from https://data.stadt-zuerich.ch/dataset/geo_fuss___und_velowegnetz

Open Data Zürich. (2024). *Züriact barrierefreie Mobilität*. Retrieved February 2, 2025, from https://data.stadt-zuerich.ch/dataset/geo_zueriact_barrierefreie_mobilitaet

Open Data Zürich. (2025). *Adressen stadt zürich*. Retrieved May 11, 2025, from https://data.stadt-zuerich.ch/dataset/geo_adressen_stadt_zuerich

OpenRouteService. (2026). *OpenRouteService maps*. Retrieved April 11, 2026, from https://maps.openrouteservice.org/

Orellana, D., Bustos, M. E., Marín-Palacios, M., Cabrera-Jara, N., & Hermida, M. A. (2020). Walk'n'roll: Mapping street-level accessibility for different mobility conditions in Cuenca, Ecuador. *Journal of Transport & Health*, *16*, 100821. https://doi.org/10.1016/j.jth.2020.100821

Ortega, E., Martín, B., López-Lambas, M. E., & Soria-Lara, J. A. (2021). Evaluating the impact of urban design scenarios on walking accessibility. *Sustainable Cities and Society*, *74*, 103156. https://doi.org/10.1016/j.scs.2021.103156

Ottoni, C. A., Sims-Gould, J., Winters, M., Heijnen, M., & McKay, H. A. (2016). "Benches become like porches": Built and social environment influences on older adults' experiences of mobility. *Social Science & Medicine*, *169*, 33–41. https://doi.org/10.1016/j.socscimed.2016.08.044

Park, J., & Chowdhury, S. (2018). Investigating the barriers in a typical journey by public transport users with disabilities. *Journal of Transport & Health*, *10*, 361–368. https://doi.org/10.1016/j.jth.2018.05.008

Paulhus, D. L., Vazire, S., et al. (2007). The self-report method. *Handbook of Research Methods in Personality Psychology*, *1*(2007), 224–239.

Penchansky, R., & Thomas, J. W. (1981). The concept of access: Definition and relationship to consumer satisfaction. *Medical care*, *19*(2), 127–140.

Portegijs, E., Keskinen, K. E., Eronen, J., Saajanaho, M., Rantakokko, M., & Rantanen, T. (2020). Older adults' physical activity and the relevance of distances to neighborhood destinations. *Frontiers in Public Health*, *8*, 335. https://doi.org/10.3389/fpubh.2020.00335

Pot, F. J., van Wee, B., & Tillema, T. (2021). Perceived accessibility: What it is and why it differs from calculated accessibility measures based on spatial data. *Journal of Transport Geography*, *94*, 103090. https://doi.org/10.1016/j.jtrangeo.2021.103090

Prescott, M., Miller, W. C., Borisoff, J., Tan, P., Garside, N., Feick, R., & Mortenson, W. B. (2021). An exploration of the navigational behaviours of people who use wheeled mobility devices in unfamiliar pedestrian environments. *Journal of Transport & Health*, *20*, 100975. https://doi.org/10.1016/j.jth.2020.100975

R Core Team. (2023). R: A language and environment for statistical computing [R Foundation for Statistical Computing, Vienna, Austria].

Rantakokko, M., Iwarsson, S., Vahaluoto, S., Portegijs, E., Viljanen, A., & Rantanen, T. (2014). Perceived environmental barriers to outdoor mobility and feelings of loneliness. *The Journals of Gerontology Series A*, *69*(12), 1562–1568. https://doi.org/10.1093/gerona/glu069

Rey-Galindo, J. A., Rizo-Corona, L., González-Muñoz, E. L., & Aceves-González, C. (2020). Environmental information for people with visual impairment in mexico-or what they need and how they use it. *Applied Ergonomics*, *85*, 103079. https://doi.org/10.1016/j.apergo.2020.103079

Rhoads, D., Rames, C., Solé-Ribalta, A., González, M. C., Szell, M., & Borge-Holthoefer, J. (2023). Sidewalk networks: Review and outlook. *Computers, Environment and Urban Systems*, *106*, 102031. https://doi.org/10.1016/j.compenvurbsys.2023.102031

Röcke, C., Luo, M., Bereuter, P., Katana, M., Fillekes, M., Gehriger, V., Sofios, A., Martin, M., & Weibel, R. (2023). Charting everyday activities in later life: Study protocol of the mobility, activity, and social interactions study (moasis). *Frontiers in Psychology, Volume 13 - 2022*. https://doi.org/10.3389/fpsyg.2022.1011177

Rohrbach, B., Anderson, S., & Laube, P. (2016). The effects of sample size on data quality in participatory mapping of past land use. *Environment and Planning B: Planning and Design*, *43*(4), 681–697. https://doi.org/10.1177/0265813515618578

Rolstad, S., Adler, J., & Rydén, A. (2011). Response burden and questionnaire length: Is shorter better? A review and meta-analysis. *Value in Health*, *14*(8), 1101–1108. https://doi.org/10.1016/j.jval.2011.06.003

Rosenberg, D. E., Huang, D. L., Simonovich, S. D., & Belza, B. (2013). Outdoor built environment barriers and facilitators to activity among midlife and older adults. *The Gerontologist*, *53*(2), 268–279. https://doi.org/10.1093/geront/gns119

Ryan, J., & Pereira, R. H. (2021). What are we missing when we measure accessibility? Comparing calculated and self-reported accounts among older people. *Journal of Transport Geography*, *93*, 103086. https://doi.org/10.1016/j.jtrangeo.2021.103086

Saha, M., Saugstad, M., Maddali, H. T., Zeng, A., Holland, R., Bower, S., Dash, A., Chen, S., Li, A., Hara, K., & Froehlich, J. (2019). Project Sidewalk: A web-based crowdsourcing tool for collecting sidewalk accessibility data at scale. *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems*, 1–14. https://doi.org/10.1145/3290605.3300292

Šakaja, L., Bašić, K., Vuk, R., Stiperski, Z., & Horvat, A. (2019). Accessibility in Zagreb for power wheelchair users. *Hrvatski Geografski Glasnik*, *81*(2), 43–68. https://doi.org/10.21861/HGG.2019.81.02.02

Sander, J., Ester, M., Kriegel, H. P., & Xu, X. (1998). Density-based clustering in spatial databases: The algorithm GDBSCAN and its applications. *Data Mining and Knowledge Discovery*, *2*, 169–194. https://doi.org/10.1023/A:1009745219419

Schönfelder, S., & Axhausen, K. W. (2003). Activity spaces: Measures of social exclusion? *Transport Policy*, *10*(4), 273–286. https://doi.org/10.1016/j.tranpol.2003.07.002

Schreuer, N., Plaut, P., Golan, L., & Sachs, D. (2019). The relations between walkable neighbourhoods and active participation in daily activities of people with disabilities. *Journal of Transport & Health*, *15*, 100630.

Schwartz, N., Buliung, R., Daniel, A., & Rothman, L. (2022). Disability and pedestrian road traffic injury: A scoping review. *Health & place*, *77*, 102896. https://doi.org/10.1016/j.healthplace.2022.102896

Schweizerischer Verband der Strassen- und Verkehrsfachleute. (2015). *Fussgängerverkehr hindernisfreier verkehrsraum* (SN 640 075:2015). Schweizerischer Verband der Strassen- und Verkehrsfachleute.

Shareck, M., Frohlich, K. L., & Kestens, Y. (2014). Considering daily mobility for a more comprehensive understanding of contextual effects on social inequalities in health: A conceptual proposal. *Health & Place*, *29*, 154–160. https://doi.org/10.1016/j.healthplace.2014.07.007

Shields, R., Gomes da Silva, E. J., Lima e Lima, T., & Osorio, N. (2023). Walkability: A review of trends. *Journal of Urbanism: International Research on Placemaking and Urban Sustainability*, *16*(1), 19–41. https://doi.org/10.1080/17549175.2021.1936601

Siła-Nowicka, K., Vandrol, J., Oshan, T., Long, J. A., Demšar, U., & Fotheringham, A. S. (2016). Analysis of human mobility patterns from GPS trajectories and contextual information. *International Journal of Geographical Information Science*, *30*(5), 881–906. https://doi.org/10.1080/13658816.2015.1100731

Sobek, A. D., & Miller, H. J. (2006). U-Access: A web-based system for routing pedestrians of differing abilities. *Journal of Geographical Systems*, *8*, 269–287. https://doi.org/10.1007/s10109-006-0021-1

Spearman, C. (1904). The proof and measurement of association between two things. *American Journal of Psychology*, *15*, 72–101. https://doi.org/10.2307/1412159

Spray, J., Witten, K., Wiles, J., Anderson, A., Paul, D., Wade, J., & Ameratunga, S. (2022). Inequitable mobilities: Intersections of diversity with urban infrastructure influence mobility, health and wellbeing. *Cities & Health*, *6*(4), 711–725. https://doi.org/10.1080/23748834.2020.1827881

Stadt Zürich. (2024). *Statistik & daten: Kreise und quartiere*. Retrieved January 6, 2026, from https://www.stadt-zuerich.ch/kreise-und-quartiere

Ståhl, A., Carlsson, G., Hovbrandt, P., & Iwarsson, S. (2008). "Let's go for a walk!": Identification and prioritisation of accessibility and safety measures involving elderly people in a residential area. *European Journal of Ageing*, *5*(3), 265–273. https://doi.org/10.1007/s10433-008-0091-7

Story, M. F. (1998). Maximizing usability: The principles of universal design. *Assistive technology*, *10*(1), 4–12. https://doi.org/10.1080/10400435.1998.10131955

Svensson, J. (2010). Accessibility in urban areas for citizens with impairments: Using GIS to map and measure accessibility in Swedish cities. In J. L. Maisel (Ed.), *The universal design: Emerging research and developments* (pp. 122–131). Bentham Publishing House. https://doi.org/10.2174/978160805063511001010122

Tajgardoon, M., & Karimi, H. A. (2015). Simulating and visualizing sidewalk accessibility for wayfinding of people with disabilities. *International Journal of Cartography*, *1*(1), 79–93. https://doi.org/10.1080/23729333.2015.1055646

Terefe, A. E., & Hou, Y. (2024). Determinants influencing the accessibility and use of urban green spaces: A review of empirical evidence. *City and Environment Interactions*, *24*, 100159. https://doi.org/10.1016/j.cacint.2024.100159

Townsend, B. G., Chen, J. T., & Wuthrich, V. M. (2021). Barriers and facilitators to social participation in older adults: A systematic literature review. *Clinical Gerontologist*, *44*(4), 359–380. https://doi.org/10.1080/07317115.2020.1863890

Tyler, N. (2006). Capabilities and radicalism: Engineering accessibility in the 21st century. *Transportation Planning and Technology*, *29*(5), 331–358. https://doi.org/10.1080/03081060600917629

United Nations. (2019). *World urbanization prospects 2018: Highlights*. UN.

United Nations. (2021). *World population ageing 2020 highlights: Living arrangements of older persons*. UN. https://books.google.ch/books?id=ApggzgEACAAJ

United Nations. (2022). The sustainable development goals report 2022. *United Nations: New York, NY, USA*.

University of Zurich. (2023). *Inclusive mobility & sustainable transport*. Geographic Information Systems, University of Zurich. Retrieved July 13, 2026, from https://www.geo.uzh.ch/en/units/gis/research/inclusive-mobility-sustainable-transport.html

Vale, D. S., Ascensão, F., Raposo, N., & Figueiredo, A. P. (2017). Comparing access for all: Disability-induced accessibility disparity in Lisbon. *Journal of Geographical Systems*, *19*(1), 43–64. https://doi.org/10.1007/s10109-016-0240-z

Van Cauwenberg, J., Van Holle, V., De Bourdeaudhuij, I., Clarys, P., Nasar, J., Salmon, J., Goubert, L., & Deforche, B. (2014). Using manipulated photographs to identify features of streetscapes that may encourage older adults to walk for transport. *PloS one*, *9*(11), e112107. https://doi.org/10.1371/journal.pone.0112107

van der Meer, L., Abad, L., Gilardi, A., & Lovelace, R. (2024). Sfnetworks: Tidy geospatial networks [R package version 0.6.5].

Völkel, T., & Weber, G. (2008). Routecheckr: Personalized multicriteria routing for mobility impaired pedestrians. *Proceedings of the 10th international ACM SIGACCESS conference on Computers and accessibility*, 185–192. https://doi.org/10.1145/1414471.1414506

VSS Zürich. (2015). *Fussgängerverkehr: Hindernisfreier verkehrsraum*.

Wazani, I. A., Mohamad, D., & Jaafar, M. (2021). Accessibility for persons with disabilities in built environment of urban area: Case study of George Town, Penang. *Planning Malaysia*, *19*. https://doi.org/10.21837/pm.v19i19.1059

Webber, S. C., Porter, M. M., & Menec, V. H. (2010). Mobility in older adults: A comprehensive framework. *The Gerontologist*, *50*(4), 443–450. https://doi.org/10.1093/geront/gnq013

Wennberg, H. (2009). *Walking in old age: A year-round perspective on accessibility in the outdoor environment and effects of measures taken* [Doctoral dissertation, Lund University].

Wennberg, H., Ståhl, A., & Hydén, C. (2009). Older pedestrians' perceptions of the outdoor environment in a year-round perspective. *European Journal of Ageing*, *6*(4), 277–290. https://doi.org/10.1007/s10433-009-0123-y

Willberg, E., Fink, C., & Toivonen, T. (2023). The 15-minute city for all?–Measuring individual and temporal variations in walking accessibility. *Journal of Transport Geography*, *106*, 103521. https://doi.org/10.1016/j.jtrangeo.2022.103521

World Health Organization. (2015). *Measuring the age-friendliness of cities: A guide to using core indicators*.

World Health Organization. (2022). *Global report on health equity for persons with disabilities*.

Xu, F., Wang, Q., Moro, E., Chen, L., Salazar Miranda, A., González, M. C., Tizzoni, M., Song, C., Ratti, C., Bettencourt, L., et al. (2025). Using human mobility data to quantify experienced urban inequalities. *Nature Human Behaviour*, *9*(4), 654–664. https://doi.org/10.1038/s41562-024-02079-0

Zheng, Y., Li, Q., Chen, Y., Xie, X., & Ma, W.-Y. (2008). Understanding mobility based on GPS data. *Proceedings of the 10th international conference on Ubiquitous computing*, 312–321. https://doi.org/10.1145/1409635.1409677

Appendix A

Supplementary Material for Chapter 2: Microscale street elements influencing spatial accessibility

A.1 Complete list of elements perceived as barriers or facilitators in included studies

Table A.1: Street elements perceived as barriers by different population groups (MWC – manual wheelchair user; PWC – powered wheelchair user; S – scooter user; WAD – walking assistive devices user; OA – older adults; VI – visually impaired individuals; SMR – situational mobility restriction).

Barrier	MWC	PWC	S	WAD	OA	VI	SMR	References
Sidewalk								
Width	✓	✓	✓	✓	✓	✓	✓	Prescott et al., 2021; Šakaja et al., 2019; Harris et al., 2015; Han et al., 2020; Wazani et al., 2021; Rosenberg et al., 2013; Campisi et al., 2021; Klicnik & Dogra, 2019; Herrmann-Lunecke et al., 2022; Orellana et al., 2020; Gao & Nagai, 2021
Slope	✓	✓	✓	✓	✓	✓	✓	Prescott et al., 2021; Han et al., 2020; Park & Chowdhury, 2018; Rosenberg et al., 2013; Campisi et al., 2021; Herrmann-Lunecke et al., 2022; Harris et al., 2015
Cross-slope	✓	✓	✓	✓		✓		Prescott et al., 2021; Park & Chowdhury, 2018; Orellana et al., 2020
Steps/Stairs	✓	✓	✓	✓	✓	✓	✓	Šakaja et al., 2019; Harris et al., 2015; Han et al., 2020; Rosenberg et al., 2013; Campisi et al., 2021; Chen et al., 2015
Obstacles – Permanent								
Height (tree branches, signs)						✓		Jenkins et al., 2015; Park & Chowdhury, 2018
Vegetation	✓	✓	✓	✓	✓	✓	✓	Park & Chowdhury, 2018; Rosenberg et al., 2013; McMullan & Butler, 2019; Han et al., 2020; Jenkins et al., 2015; Van Cauwenberg et al., 2014
Street infrastructure/furniture	✓	✓	✓	✓	✓	✓		Wazani et al., 2021; Park & Chowdhury, 2018; Rosenberg et al., 2013; Cushley et al., 2022; Rey-Galindo et al., 2020; Campisi et al., 2021
Architectural features						✓		Rey-Galindo et al., 2020
Street vendors					✓	✓		Herrmann-Lunecke et al., 2022; Rey-Galindo et al., 2020
Obstacles – Temporary								
Parked vehicles	✓	✓	✓	✓	✓	✓		Wazani et al., 2021; Park & Chowdhury, 2018; Rosenberg et al., 2013; Herrmann-Lunecke et al., 2022; Chen et al., 2015; Cushley et al., 2022
Garbage	✓	✓			✓	✓		Wazani et al., 2021
Construction	✓	✓		✓	✓	✓		McMullan & Butler, 2019; Park & Chowdhury, 2018; Klicnik & Dogra, 2019
Sidewalk smoothness								

Barrier	MWC	PWC	S	WAD	OA	VI	SMR	References
Uneven sidewalk	✓	✓	✓	✓	✓	✓	✓	Jenkins et al., 2015; Campisi et al., 2021; Park & Chowdhury, 2018; Han et al., 2020; Aldersey et al., 2018; Rosenberg et al., 2013; Van Cauwenberg et al., 2014; Harris et al., 2015; Prescott et al., 2011; Chen et al., 2015; Wazani et al., 2021; Orellana et al., 2020; Rey-Galindo et al., 2020
Lack of maintenance						✓		Campisi et al., 2021
Grass/debris	✓	✓	✓	✓	✓	✓		Cushley et al., 2022; Rosenberg et al., 2013; Herrmann-Lunecke et al., 2022
Sidewalk material								
Brick/pavers	✓	✓	✓	✓				Rosenberg et al., 2013; Harris et al., 2015
Unpaved	✓	✓	✓	✓				Rosenberg et al., 2013; Harris et al., 2015
Hard surfaces					✓			Herrmann-Lunecke et al., 2022
Soft surfaces					✓			Chen et al., 2015
Ramps improperly designed	✓	✓	✓	✓				Harris et al., 2015; Aldersey et al., 2018; Rosenberg et al., 2013
Drain grates	✓	✓	✓					Harris et al., 2015
Tactile paving	✓	✓		✓				Park & Chowdhury, 2018
Undulating footpath	✓	✓	✓	✓		✓		Park & Chowdhury, 2018; Rosenberg et al., 2013
Poor street lighting	✓	✓	✓	✓	✓	✓		Park & Chowdhury, 2018; Cushley et al., 2022; Jenkins et al., 2015; Rosenberg et al., 2013
Pavement congestion		✓			✓	✓		Šakaja et al., 2019; Herrmann-Lunecke et al., 2022; McMullan & Butler, 2019; Rey-Galindo et al., 2020
Crosswalk								
High kerbs	✓	✓	✓	✓	✓	✓		Šakaja et al., 2019; Harris et al., 2015; Aldersey et al., 2018; Wazani et al., 2021; Rosenberg et al., 2013; Klicnik & Dogra, 2019; McMullan & Butler, 2019
Inappropriate kerb ramps	✓	✓	✓	✓	✓	✓		Prescott et al., 2021; Orellana et al., 2020; Harris et al., 2015; Park & Chowdhury, 2018; Wazani et al., 2021; Rosenberg et al., 2013; Jenkins et al., 2015
Lowered kerbs						✓		Han et al., 2020
Crossing time too short	✓	✓	✓	✓	✓			Wazani et al., 2021; Rosenberg et al., 2013
Poor marking	✓	✓	✓	✓	✓			Wazani et al., 2021; Rosenberg et al., 2013; Harris et al., 2015
High traffic speed	✓	✓	✓	✓	✓			Wazani et al., 2021; Rosenberg et al., 2013
Pedestrian/Open areas								
Shared spaces	✓	✓	✓	✓	✓	✓		Cushley et al., 2022; Chen et al., 2015; Herrmann-Lunecke et al., 2022; Han et al., 2020; Van Cauwenberg et al., 2014; Gao & Nagai, 2021; Rosenberg et al., 2013
Lack of								
Sidewalk	✓	✓	✓	✓		✓		Orellana et al., 2020; Harris et al., 2015; Park & Chowdhury, 2018; Aldersey et al., 2018; Rosenberg et al., 2013
Shelter	✓	✓	✓	✓	✓	✓		Wazani et al., 2021; Rosenberg et al., 2013
Places to rest	✓	✓	✓	✓	✓	✓		Wazani et al., 2021; Rosenberg et al., 2013; Klicnik & Dogra, 2019; Herrmann-Lunecke et al., 2022; Gao & Nagai, 2021
Pedestrian crossings	✓	✓	✓	✓	✓	✓		Park & Chowdhury, 2018; Wazani et al., 2021; Rosenberg et al., 2013; Klicnik & Dogra, 2019

Table A.2: Street elements perceived as facilitators by different population groups (MWC – manual wheelchair user; PWC – powered wheelchair user; S – scooter user; WAD – walking assistive devices user including walker, rollator, walking stick and crutches; OA – older adults; VI – visually impaired individuals; SMR – individuals with situational mobility restriction including people using pushchairs).

Facilitator	MWC	PWC	S	WAD	OA	VI	SMR	References
Sidewalk								
Presence of sidewalk	✓	✓	✓	✓				Rosenberg et al., 2013
Wide sidewalks	✓	✓	✓	✓	✓			Rosenberg et al., 2013; Herrmann-Lunecke et al., 2022; Gao & Nagai, 2021
Good sidewalk conditions (paved, smooth, concrete)	✓	✓	✓	✓	✓			Aldersey et al., 2018; Rosenberg et al., 2013; Gao & Nagai, 2021
Flat sidewalk / gentle slope	✓	✓	✓	✓		✓		Rosenberg et al., 2013; McMullan & Butler, 2019
Separation from traffic		✓			✓	✓	✓	Van Cauwenberg et al., 2014; Gao & Nagai, 2021; Han et al., 2020
Hedged footpath					✓			Gao & Nagai, 2021; Van Cauwenberg et al., 2014
Clean environment					✓			Herrmann-Lunecke et al., 2022
Ramps (properly designed)	✓	✓	✓	✓			✓	Rosenberg et al., 2013; Han et al., 2020; Aldersey et al., 2018
No parked cars					✓			Gao & Nagai, 2021
Benches	✓	✓	✓	✓	✓			Rosenberg et al., 2013; Ottoni et al., 2016; Herrmann-Lunecke et al., 2022; Van Cauwenberg et al., 2014; Gao & Nagai, 2021
Covered/sheltered areas	✓	✓	✓	✓				Rosenberg et al., 2013
Adequate lighting	✓	✓	✓	✓				Rosenberg et al., 2013
Textured landmarks						✓		Jenkins et al., 2015
Handrails with braille						✓		Han et al., 2020
Auditory landmarks (echoes, sounds)						✓		Jenkins et al., 2015
Tactile paving						✓		Han et al., 2020
Tactile/auditory signage						✓		Han et al., 2020
Gaps in sidewalk						✓		Rey-Galindo et al., 2020
Crosswalks								
Lowered kerb ramps	✓	✓	✓	✓		✓	✓	Rosenberg et al., 2013; Han et al., 2020; McMullan & Butler, 2019
Kerbs						✓		Rey-Galindo et al., 2020
Lots of crosswalks	✓	✓	✓	✓				Rosenberg et al., 2013
Clearly marked crosswalks	✓	✓	✓	✓		✓		Rosenberg et al., 2013; McMullan & Butler, 2019
Shared pathways (few road crossings)						✓		McMullan & Butler, 2019
Underpasses						✓		McMullan & Butler, 2019
Accessible pedestrian signals (APS)						✓		Han et al., 2020; Jenkins et al., 2015

Appendix B

Supplementary Material for Chapter 3: How mobility restrictions shape perceptions of pedestrian infrastructure

B.1 Questionnaire

This section of this appendix presents the questionnaire used in in-person and online surveys. The questions were designed to assess participants' perceptions of microscale street elements and their influence on walking difficulty and facilitation.

Part 1 – Participant Information

1. Select the group with which you most identify:
   a. Individuals with mobility impairments ☐
   b. Individuals with visual impairments ☐
   c. Individuals over 65 years of age with mobility restrictions ☐
   d. Individuals experiencing situational mobility restrictions ☐
   e. Other: _____

2. First and Last name: _____

3. E-mail address: _____

4. Age: _____

5. Postcode: _____

6. Please choose the gender you most identify with:
   Female ☐ Male ☐ Other ☐ No response ☐

7. What is the highest level of education you have completed?
   a. No school or vocational training ☐
   b. Compulsory education ☐
   c. Apprenticeship or vocational school ☐
   d. Upper secondary school ☐
   e. Higher degree ☐
   f. No response ☐

8. In which area of the following income groups are your own monthly net incomes?
   a. Up to 3'000 Fr. ☐
   b. 3'001–4'000 Fr. ☐
   c. 4'001–6'000 Fr. ☐
   d. 6'001–8'000 Fr. ☐
   e. 8'001–12'000 Fr. ☐
   f. More than 12'000 Fr. ☐
   g. No response ☐

9. Do you use any of the following mobility assistive devices in your daily life? Please choose all that apply:
    - Manual wheelchair ☐
    - Electric wheelchair ☐
    - Scooter ☐
    - Walker ☐
    - Rollator ☐
    - Walking stick ☐
    - White cane ☐
    - Assistance dog ☐
    - None ☐
    - Other: _____

10. If multiple devices were chosen in the previous question, what is the main mobility assistive device used?
    - Manual wheelchair ☐
    - Electric wheelchair ☐
    - Scooter ☐
    - Walker ☐
    - Rollator ☐
    - Walking stick ☐
    - White cane ☐
    - Assistance dog ☐
    - None ☐
    - Other: _____

11. Please indicate whether your mobility restriction is/was:
    - Temporary (still limited) ☐
    - Temporary (no longer affected) ☐
    - Permanent ☐

12. Please indicate how many years you have been affected by your mobility restrictions:
    - Since birth ☐
    - Years: _____

13. Which is the main mode of transportation you use in a typical week?
    - Walking/wheeling (alone) ☐
    - Walking/wheeling (with assistance) ☐
    - Car ☐
    - Special transport ☐
    - Public transport ☐
    - Other: _____

14. How many times do you walk/wheel for transport in a typical week (i.e., to reach a public facility such as a grocery store, to go to work, etc.)?
    - Never ☐
    - Rarely ☐
    - Occasionally ☐
    - Frequently ☐
    - Very frequently ☐

15. How many times do you walk/wheel for leisure in a typical week?
    - Never ☐
    - Rarely ☐
    - Occasionally ☐
    - Frequently ☐
    - Very frequently ☐

16. What is the main reason for which you walk/wheel in a typical week?
    - Convenience ☐
    - Health ☐
    - Cost efficiency ☐
    - Lack of alternatives ☐
    - Accessibility ☐
    - Enjoyment ☐
    - Social interaction ☐
    - Other: _____

Part 2 – Barriers

1. Select from the list below the street elements that represent barriers and hinder your daily mobility: (Barrier = a street element that makes it difficult to use the sidewalk)
    - Narrow sidewalk ☐
    - Steep sidewalk ☐
    - Cross-slope ☐
    - Small-scale obstacles ☐
    - Large-scale obstacles ☐
    - Steps/Stairs ☐
    - Material type ☐
    - Uneven sidewalk ☐
    - High kerbs ☐
    - No zebra crossing ☐
    - No accessible signals ☐
    - Tram tracks ☐
    - Long crosswalk ☐
    - Crosswalk surface problems ☐
    - Paint fading ☐
    - Shared spaces ☐
    - Lack of rest areas ☐

- Missing sidewalk ☐
- Lack of street lights ☐
- Other: _____

2. Rate the following street elements based on the level of severity they have in your daily mobility:
   Fully passable = The street element could represent a problem, however it should be fully passable to you.
   Almost fully passable = The street element requires you to slow down and deviate a bit from it, but without too much effort.
   Passable = The street element represents a problem for you, but you are still capable of overcoming it alone by reducing your speed, stopping or changing the route.
   Almost not passable = You can pass the street element, but with some risk, a lot of effort, or with help.
   Not passable = You cannot pass this street element at all.

Street element	Fully passable	Almost fully passable	Passable	Almost not passable	Not passable
Narrow sidewalk					
Steep sidewalk					
Cross-slope					
Small obstacles					
Large obstacles					
Steps/Stairs					
Material type					
Uneven sidewalk					
High kerbs					
No zebra crossings					
No signals					
Tram tracks					
Long crosswalks					
Surface problems					
Paint fading					
Shared spaces					
Lack of rest					
Missing sidewalk					
Lack of lighting					

Part 3 – Facilitators

1. Select from the list below the street elements that facilitate your daily mobility: (Facilitator = a street element that makes movement through the urban environment easier).
   - Wide sidewalk ☐
   - Flat sidewalk ☐
   - Smooth sidewalk ☐
   - Separated pedestrian space ☐
   - Lowered kerbs ☐
   - Zebra crossing ☐
   - Accessible signals ☐
   - Benches ☐
   - Adequate lighting ☐
   - Other: _____

2. Rate the following street elements based on their level of facilitation in your daily mobility:

Street element	Very facilitating	Facilitating	Neutral	Not really facilitating	Not facilitating
Wide sidewalk					
Flat sidewalk					
Smooth sidewalk					
Separated space					
Lowered kerbs					
Zebra crossing					
Signals					
Benches					
Lighting					

Part 4 – Accessibility of the environment

1. How accessible do you think your neighbourhood is?

   (a) Sidewalk
   - Very accessible ☐
   - Somewhat accessible ☐
   - Neutral ☐
   - Somewhat inaccessible ☐
   - Not accessible ☐
   - Not sure ☐

   (b) Crosswalk
   - Very accessible ☐
   - Somewhat accessible ☐
   - Neutral ☐
   - Somewhat inaccessible ☐

- Not accessible ☐
- Not sure ☐

(c) Pedestrian areas (i.e., areas designed for walking, prioritising pedestrians with limited vehicles)
- Very accessible ☐
- Somewhat accessible ☐
- Neutral ☐
- Somewhat inaccessible ☐
- Not accessible ☐
- Not sure ☐

2. What is the main reason you avoid walking/wheeling around your neighbourhood/district?
   - Barriers ☐
   - Safety concerns ☐
   - Lack of facilities ☐
   - Lack of attractiveness ☐
   - Other: _____

3. How much do you feel the built environment (e.g., the sidewalk, the crosswalks or the pedestrian areas) in your neighbourhood limits your movement through space?
   - Not at all ☐
   - Slightly ☐
   - Moderately ☐
   - Very ☐
   - Extremely ☐

Questionnaire screenshots

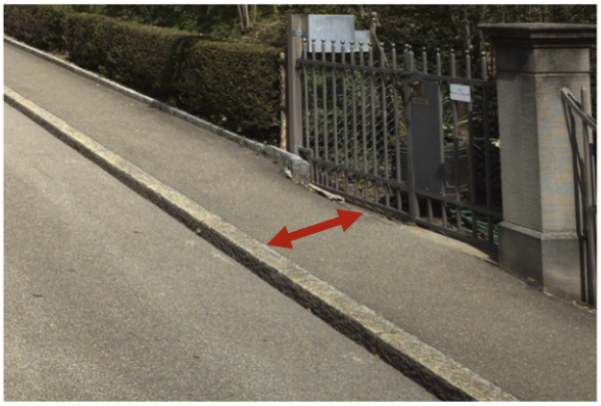
The following screenshots illustrate examples of the online questionnaire and how the questions were presented to participants.

*Select from the list below the street elements that represent barriers and hinder your daily mobility:

(Barrier = a street element that makes it difficult to use the sidewalk)

Note: The same street elements will appear repeatedly throughout this section of the questionnaire as possible barriers. Each question, however, focuses on different aspects with regard to these elements.

☐ Narrow sidewalk



☐ Steep sidewalk



☐ Large-scale obstacles (e.g., tree, vegetation, outdoor dining area, constructions, parked cars, etc.)



☐ Stairs/steps



*Rate the following street elements based on the **level of severity** they have in your daily mobility:

(Fully passable = The street element could represent a problem, however it should be fully passable to you.

Almost fully passable = The street element requires you to slow down and deviate a bit from it but without too much effort.

Passable = The street element represents a problem for you but you are still capable of overcoming it alone by reducing your speed, stopping or changing the route.

Almost not passable = You can pass the street element but with some risk or a lot of effort or with help.

Not passable = You cannot pass this street element at all.)

If you do not perceive a street element as a barrier please choose "Fully pasable".

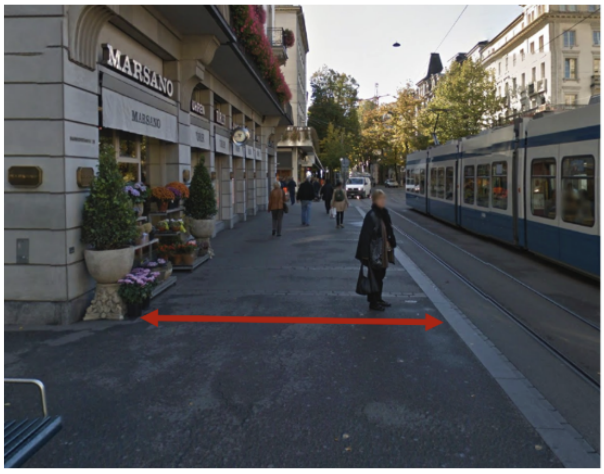
	Fully passable	**Almost fully passable**	**Passable with some difficulty**	**Almost not passable**	**Not passable**
Narrow sidewalk	○	○	○	○	○
Steep sidewalk	○	○	○	○	○
Cross-slope	○	○	○	○	○
Small-scale obstacles (e.g., pole, trash/recycling can, sign, parked bikes, parked motorcycles, trash can, litter/garbage, fire hydrant, etc.)	○	○	○	○	○
Large-scale obstacles (e.g., tree, vegetation, outdoor dining area, constructions, parked cars, etc.)	○	○	○	○	○

*Select from the list below the street elements that facilitate your daily mobility:

(Facilitator = a street element that makes movement through the urban environment easier)

Note: The same street elements will appear repeatedly throughout this section of the questionnaire as possible facilitator. Each question, however, focuses on different aspects with regard to these elements.

☐ Wide sidewalk



☐ Separated space for pedestrians



*Rate the following street elements based on their **level of facilitation** in your daily mobility:

	Very facilitating	Facilitating	Neutral	Rather not facilitating	Not facilitating
Wide sidewalk	○	○	○	○	○
Flat sidewalk	○	○	○	○	○
Smooth sidewalk	○	○	○	○	○
Separated space for pedestrians	○	○	○	○	○
Lowered kerbs	○	○	○	○	○
Zebra crosswalks	○	○	○	○	○
Accessible signals at crosswalks	○	○	○	○	○
Benches / Places to rest	○	○	○	○	○
Adequete street lighting	○	○	○	○	○

B.2 Microscale street elements

Table B.1: Definition of microscale street elements classified as barriers and facilitators.

Element	Explanation
Barriers	
Narrow sidewalk	A sidewalk whose clear width is insufficient to comfortably accommodate pedestrian flow or the use of mobility assistive devices such as wheelchairs, walkers, or strollers.
Steep sidewalk	A sidewalk segment with a noticeable longitudinal or transverse slope that requires increased physical effort to traverse.
Uneven sidewalk	A sidewalk surface with irregularities such as cracks, bumps, potholes, raised slabs, or manholes that impede smooth walking or wheeling.
Sidewalk material type	The surface material used to pave the sidewalk (e.g., cobblestone, natural stone, asphalt, concrete) that may affect stability, traction, or comfort.
Small-scale obstacles	Minor physical obstructions along the pedestrian route that partially impede movement or reduce the effective clear width of the sidewalk (e.g. trash/recycling bins, signs, parked bicycles, parked motorcycles, trash/rubbish, fire hydrants, etc.).
Large-scale obstacles	Major physical obstructions along the pedestrian route that substantially block, redirect, or interrupt pedestrian movement over a longer distance (e.g. trees, vegetation, outdoor dining areas, construction sites, parked cars, etc.).
Lack of places to rest	Extended sidewalk segments without benches, seating, or resting opportunities for pedestrians.
Stairs	One or more steps along the pedestrian route.
High kerb	A raised kerb at a crossing or street edge without a ramp or lowered kerb, creating a vertical barrier between sidewalk and roadway.
No accessible signals at intersection	Intersections lacking pedestrian traffic signals, push buttons, audible cues, or other assistive features for safe and accessible crossing.
Shared pedestrian space	Areas where pedestrians share space with other travel modes (e.g., cyclists or vehicles) and do not have physical separation or clear priority.
Missing sidewalk	Street segments where no designated pedestrian sidewalk is present, forcing pedestrians to walk on the road.
Lack of street lighting	Insufficient or absent lighting along the sidewalk or crossing, reducing visibility and perceived safety.
Crossing surface problem	Defects or irregularities in the crossing surface, such as cracks, potholes, uneven paving, or damaged materials.
Tram tracks at crossing	Tram tracks intersecting pedestrian crossings that may create gaps, uneven surfaces, or tripping hazards.
Long crossing	A crossing requiring an extended distance, increasing exposure time to traffic and physical effort.
Faded zebra crossing markings	Poorly visible or worn crossing markings.
No zebra crossing	Absence of clearly marked pedestrian crossing areas indicating pedestrian priority.
Facilitators	
Wide sidewalk	A sidewalk with sufficient clear width to allow comfortable pedestrian movement and the use of mobility assistive devices.
Flat sidewalk	A sidewalk segment without noticeable slopes, facilitating easier walking and wheeling.
Smooth sidewalk	A sidewalk surface free of bumps, cracks, manholes, or uneven materials.
Separated pedestrian space	Clear physical separation between pedestrian paths and other travel modes using kerbs, vegetation, bollards, or level differences.
Lowered kerb	Kerbs with a gentle slope that provide a smooth transition between sidewalk and road at crossings.
Accessible signals at intersection	Crossings equipped with zebra markings, pedestrian traffic signals, push buttons, and audible or tactile cues.
Places to rest	Availability of benches, chairs, or other seating options along the pedestrian route.
Adequate street lighting	Sufficient and evenly distributed lighting that enhances visibility, safety, and comfort along sidewalks and crossings.
Zebra crossing	Clearly marked pedestrian crossings indicating pedestrian priority and improving crossing safety.

B.3 Survey participants

Table B.2: Demographic and mobility-related characteristics of participants by study group.

	Mobility-impaired N=30	**Older adults** N=30	**Situationally restricted** N=30	**Visually impaired** N=30
Age mean (range)	39.9 (22–71)	80.7 (65–98)	40.7 (21–72)	43.5 (19–76)
Aged > 65 years old	2	30	1	4
Gender				
Woman	17 (56.7%)	20 (66.7%)	19 (63.4%)	21 (70.0%)
Man	10 (33.3%)	10 (33.3%)	9 (30.0%)	9 (30.0%)
Other	3 (10.0%)	0	1 (3.3%)	0
Prefer not to say	0	0	1 (3.3%)	0
Education				
Compulsory education (Primary/Secondary school)	2 (6.7%)	5 (16.7%)	0	2 (6.7%)
Upper secondary school	7 (23.3%)	1 (3.3%)	2 (6.7%)	3 (10%)
Apprenticeship or full-time vocational school	9 (30.0%)	13 (43.3%)	6 (20.0%)	10 (33.3%)
Higher degree (HF/FH/University)	11 (36.7%)	8 (26.7%)	21 (70.0%)	15 (50%)
Prefer not to say	1 (3.3%)	3 (10%)	1 (3.3%)	0
Income				
Up to 3'000 Fr.	11 (36.7%)	4 (13.3%)	6 (20.0%)	7 (23.3%)
3'001 to 4'000 Fr.	2 (6.7%)	6 (20%)	4 (13.3%)	4 (13.3%)
4'001 to 6'000 Fr.	5 (16.7%)	2 (6.7%)	10 (33.3%)	6 (20%)
6'001 to 8'000 Fr.	2 (6.7%)	2 (6.7%)	6 (20.0%)	3 (10%)
8'001 to 12'000 Fr.	2 (6.7%)	5 (16.7%)	0	1 (3.3%)
Prefer not to say	8 (26.7%)	11 (36.7%)	4 (13.3%)	8 (26.7%)
Most used mobility assistive device				
Assistance dog	0	0	0	2 (6.7%)
Crutches	0	0	1 (3.3%)	0
Edge filter glasses	0	2 (6.7%)	0	0
Electric wheelchair	7 (23.3%)	1 (3.3%)	1 (3.3%)	0
Manual wheelchair	13 (43.3%)	3 (10%)	0	0
Manual wheelchair with power add-on	5 (16.7%)	0	0	0
Rollator	0	6 (20%)	0	0
Scooter	1 (3.3%)	0	0	0
Shopping trolley	0	2 (6.7%)	0	0
Stroller	0	0	4 (13.3%)	0
Walker	1 (3.3%)	2 (6.7%)	3 (10.0%)	0
Walking stick	1 (3.3%)	6 (20%)	0	1 (3.3%)
White cane	1 (3.3%)	1 (3.3%)	1 (3.3%)	20 (66.7%)
White cane and assistance dog	0	0	0	1 (3.3%)
None	1 (3.3%)	6 (20%)	19 (63.3%)	6 (20.0%)
Main transport mode used				
Walking/wheeling (alone)	8 (26.7%)	5 (16.7%)	3 (10.0%)	4 (13.3%)
Walking/wheeling (with guide or family)	0	0	5 (16.7%)	0
Special transport services	5 (16.7%)	2 (6.7%)	0	0
Public transport	13 (43.3%)	12 (40%)	21 (70.0%)	26 (86.7%)
Car	1 (3.3%)	6 (20%)	0	0
Frequency of walking/wheeling for transport				
Never	0	4 (13.3%)	0	0
Rarely (1–2 times)	7 (23.3%)	7 (23.3%)	4 (13.3%)	4 (13.3%)
Occasionally (3–4 times)	4 (13.3%)	9 (30%)	9 (30%)	4 (13.3%)
Frequently (5–6 times)	7 (23.3%)	7 (23.3%)	11 (36.7%)	12 (40%)
Very frequently (7+)	12 (40%)	3 (10%)	6 (20%)	10 (33.3%)
Frequency of walking/wheeling for leisure				
Never	2 (6.7%)	2 (6.7%)	1 (3.3%)	2 (6.7%)
Rarely (1–2 times)	5 (16.7%)	10 (33.3%)	9 (30%)	10 (33.3%)
Occasionally (3–4 times)	11 (36.7%)	10 (33.3%)	15 (50%)	10 (33.3%)
Frequently (5–6 times)	6 (20%)	6 (20%)	5 (16.7%)	6 (20%)
Very frequently (7+)	6 (20%)	2 (6.7%)	0	2 (6.7%)
Main reason for walking/wheeling				
Accessibility to nearby destinations	14 (46.7%)	6 (20%)	11 (36.7%)	4 (13.3%)
Community interaction	1 (3.3%)	3 (10%)	4 (13.3%)	1 (3.3%)
Cost-effectiveness	2 (6.7%)	2 (6.7%)	1 (3.3%)	3 (10%)
Enjoy scenery	1 (3.3%)	2 (6.7%)	1 (3.3%)	1 (3.3%)
Health/exercise	4 (13.3%)	10 (33.3%)	4 (13.3%)	7 (23.3%)
Lack of alternative transportation options	4 (13.3%)	1 (3.3%)	1 (3.3%)	4 (13.3%)
Convenient	1 (3.3%)	3 (10%)	8 (26.7%)	3 (10%)

	Mobility-impaired N=30	**Older adults** N=30	**Situationally restricted** N=30	**Visually impaired** N=30
Other	3 (10%)	2 (6.7%)	0	6 (20%)
Main reason to avoid walking/wheeling				
Barriers	10 (33.3%)	6 (20%)	8 (26.7%)	13 (43.3%)
Lack of POIs	3 (10%)	3 (10%)	8 (26.7%)	3 (10%)
Lack of attractiveness	4 (13.3%)	3 (10%)	6 (20%)	3 (10%)
Not safe/secure	3 (10%)	7 (23.3%)	2 (6.7%)	4 (13.3%)
Other	10 (33.3%)	7 (23.3%)	5 (16.7%)	7 (23.3%)
Built environment limitation				
Not at all	6 (20%)	13 (43.3%)	9 (30%)	9 (30%)
Slightly	10 (33.3%)	9 (30%)	15 (50%)	9 (30%)
Moderately	5 (16.7%)	7 (23.3%)	4 (13.3%)	8 (26.7%)
Very	8 (26.7%)	1 (3.3%)	2 (6.7%)	4 (13.3%)
Extremely	1 (3.3%)	0	0	0

B.4 Between-groups variation

Dunn test - Barriers

Table B.3 presents the full results of the Dunn post hoc tests for barriers, complementing the summary findings reported in the main text.

Table B.3: Pairwise post hoc comparisons using Dunn's test of perceived walking difficulty associated with selected microscale street elements across mobility-impaired individuals (MI), mobility-restricted adults aged 65 years and older (OA), situationally restricted individuals (SR), and visually impaired individuals (VI). The table reports test statistics, adjusted p-values, significance levels, and Vargha–Delaney A (VDA) effect sizes.

Microscale street element	G1	G2	n_1	n_2	stat	p	p_{adj}	sig.	VDA
Narrow sidewalk	MI	OA	30	30	-2.227	0.026	0.13	ns	0.667
Narrow sidewalk	MI	SR	30	30	-2.152	0.031	0.13	ns	0.657
Narrow sidewalk	MI	VI	30	30	-3.21	0.001	0.008	**	0.722
Narrow sidewalk	OA	SR	30	30	0.075	0.94	0.94	ns	0.494
Narrow sidewalk	OA	VI	30	30	-0.983	0.325	0.87	ns	0.578
Narrow sidewalk	SR	VI	30	30	-1.058	0.29	0.87	ns	0.578
Steep sidewalk	MI	OA	30	30	-0.004	0.997	0.997	ns	0.513
Steep sidewalk	MI	SR	30	30	-2.745	0.006	0.024	*	0.703
Steep sidewalk	MI	VI	30	30	-4.892	0	0	***	0.836
Steep sidewalk	OA	SR	30	30	-2.741	0.006	0.024	*	0.711
Steep sidewalk	OA	VI	30	30	-4.888	0	0	***	0.853
Steep sidewalk	SR	VI	30	30	-2.147	0.032	0.064	ns	0.672
Cross-slope	MI	OA	30	30	-0.146	0.884	0.884	ns	0.513
Cross-slope	MI	SR	30	30	-1.945	0.052	0.207	ns	0.646
Cross-slope	MI	VI	30	30	-3.362	0.001	0.005	**	0.734
Cross-slope	OA	SR	30	30	-1.799	0.072	0.216	ns	0.637
Cross-slope	OA	VI	30	30	-3.216	0.001	0.006	**	0.727
Cross-slope	SR	VI	30	30	-1.417	0.156	0.313	ns	0.615
Small-scale obstacles	MI	OA	30	30	-1.849	0.065	0.258	ns	0.636
Small-scale obstacles	MI	SR	30	30	-3.164	0.002	0.009	**	0.702
Small-scale obstacles	MI	VI	30	30	-0.248	0.805	0.805	ns	0.54
Small-scale obstacles	OA	SR	30	30	-1.315	0.189	0.377	ns	0.616
Small-scale obstacles	OA	VI	30	30	1.601	0.109	0.328	ns	0.367
Small-scale obstacles	SR	VI	30	30	2.916	0.004	0.018	*	0.287
Large-scale obstacles	MI	OA	30	30	-2.769	0.006	0.025	*	0.704
Large-scale obstacles	MI	SR	30	30	-2.809	0.005	0.025	*	0.694
Large-scale obstacles	MI	VI	30	30	-3.046	0.002	0.014	*	0.726
Large-scale obstacles	OA	SR	30	30	-0.04	0.968	1	ns	0.507
Large-scale obstacles	OA	VI	30	30	-0.277	0.782	1	ns	0.52
Large-scale obstacles	SR	VI	30	30	-0.236	0.813	1	ns	0.512
Stairs	MI	OA	30	30	-3.414	0.001	0.003	**	0.781
Stairs	MI	SR	30	30	-3	0.003	0.005	**	0.738
Stairs	MI	VI	30	30	-6.61	0	0	***	0.921
Stairs	OA	SR	30	30	0.414	0.679	0.679	ns	0.459
Stairs	OA	VI	30	30	-3.197	0.001	0.004	**	0.777
Stairs	SR	VI	30	30	-3.61	0	0.002	**	0.771
Sidewalk material type	MI	OA	30	29	-0.336	0.737	0.737	ns	0.532
Sidewalk material type	MI	SR	30	30	-4.415	0	0	***	0.786
Sidewalk material type	MI	VI	30	30	-2.029	0.042	0.127	ns	0.649
Sidewalk material type	OA	SR	29	30	-4.041	0	0	***	0.808
Sidewalk material type	OA	VI	29	30	-1.676	0.094	0.188	ns	0.648
Sidewalk material type	SR	VI	30	30	2.386	0.017	0.068	ns	0.311
Uneven sidewalk	MI	OA	30	30	-1.099	0.272	0.51	ns	0.581
Uneven sidewalk	MI	SR	30	30	-4.324	0	0	***	0.795
Uneven sidewalk	MI	VI	30	30	-2.238	0.025	0.101	ns	0.672
Uneven sidewalk	OA	SR	30	30	-3.225	0.001	0.006	**	0.729
Uneven sidewalk	OA	VI	30	30	-1.138	0.255	0.51	ns	0.586
Uneven sidewalk	SR	VI	30	30	2.086	0.037	0.111	ns	0.335
High kerb	MI	OA	30	28	-3.535	0	0.002	**	0.765
High kerb	MI	SR	30	30	-4.959	0	0	***	0.864
High kerb	MI	VI	30	30	-6.013	0	0	***	0.886
High kerb	OA	SR	28	30	-1.338	0.181	0.362	ns	0.656

Microscale street element	G1	G2	n_1	n_2	stat	p	p_{adj}	sig.	VDA
High kerb	OA	VI	28	30	-2.373	0.018	0.053	ns	0.721
High kerb	SR	VI	30	30	-1.054	0.292	0.362	ns	0.608
No accessible signals at intersections	MI	OA	30	30	0.421	0.674	1	ns	0.459
No accessible signals at intersections	MI	SR	30	30	-0.37	0.711	1	ns	0.524
No accessible signals at intersections	MI	VI	30	30	3.914	0	0	***	0.232
No accessible signals at intersections	OA	SR	30	30	-0.791	0.429	1	ns	0.567
No accessible signals at intersections	OA	VI	30	30	3.493	0	0.002	**	0.229
No accessible signals at intersections	SR	VI	30	30	4.284	0	0	***	0.202
Tram tracks at crossings	MI	OA	30	30	-1.722	0.085	0.34	ns	0.627
Tram tracks at crossings	MI	SR	30	30	-3.424	0.001	0.004	**	0.729
Tram tracks at crossings	MI	VI	30	30	-0.434	0.664	0.664	ns	0.543
Tram tracks at crossings	OA	SR	30	30	-1.702	0.089	0.34	ns	0.632
Tram tracks at crossings	OA	VI	30	30	1.288	0.198	0.396	ns	0.401
Tram tracks at crossings	SR	VI	30	30	2.99	0.003	0.014	*	0.282
Long crossing	MI	OA	30	30	0.178	0.859	1	ns	0.498
Long crossing	MI	SR	30	30	-2.471	0.013	0.054	ns	0.657
Long crossing	MI	VI	30	30	0.706	0.48	1	ns	0.458
Long crossing	OA	SR	30	30	-2.649	0.008	0.04	*	0.709
Long crossing	OA	VI	30	30	0.528	0.597	1	ns	0.454
Long crossing	SR	VI	30	30	3.177	0.001	0.009	**	0.271
Crossing surface problems	MI	OA	30	30	0.031	0.975	0.975	ns	0.518
Crossing surface problems	MI	SR	30	30	-3.48	0.001	0.003	**	0.719
Crossing surface problems	MI	VI	30	30	-0.983	0.325	0.931	ns	0.578
Crossing surface problems	OA	SR	30	30	-3.512	0	0.003	**	0.758
Crossing surface problems	OA	VI	30	30	-1.014	0.31	0.931	ns	0.584
Crossing surface problems	SR	VI	30	30	2.497	0.013	0.05	ns	0.302
Faded zebra crossing markings	MI	OA	30	30	2.122	0.034	0.109	ns	0.36
Faded zebra crossing markings	MI	SR	30	30	-0.085	0.932	0.932	ns	0.503
Faded zebra crossing markings	MI	VI	30	30	2.852	0.004	0.022	*	0.325
Faded zebra crossing markings	OA	SR	30	30	-2.207	0.027	0.109	ns	0.648
Faded zebra crossing markings	OA	VI	30	30	0.73	0.465	0.931	ns	0.442
Faded zebra crossing markings	SR	VI	30	30	2.937	0.003	0.02	*	0.318
Shared pedestrian spaces	MI	OA	30	29	1.362	0.173	0.52	ns	0.388
Shared pedestrian spaces	MI	SR	30	30	0.267	0.789	0.789	ns	0.472
Shared pedestrian spaces	MI	VI	30	30	3.321	0.001	0.005	**	0.267
Shared pedestrian spaces	OA	SR	29	30	-1.097	0.273	0.545	ns	0.593
Shared pedestrian spaces	OA	VI	29	30	1.931	0.054	0.214	ns	0.382
Shared pedestrian spaces	SR	VI	30	30	3.054	0.002	0.011	*	0.27
Missing sidewalk	MI	OA	30	30	-2.659	0.008	0.047	*	0.687
Missing sidewalk	MI	SR	30	30	-2.516	0.012	0.059	ns	0.675
Missing sidewalk	MI	VI	30	30	-1.586	0.113	0.451	ns	0.632
Missing sidewalk	OA	SR	30	30	0.143	0.886	0.886	ns	0.494
Missing sidewalk	OA	VI	30	30	1.074	0.283	0.849	ns	0.41
Missing sidewalk	SR	VI	30	30	0.931	0.352	0.849	ns	0.428

Dunn test - Facilitators

Table B.4 presents the full results of the Dunn post hoc tests for facilitators, complementing the summary findings reported in the main text.

Table B.4: Pairwise post hoc comparisons using Dunn's test of perceived walking facilitation associated with selected microscale street elements across mobility-impaired individuals (MI), mobility-restricted adults aged 65 years and older (OA), situationally restricted individuals (SR), and visually impaired individuals (VI). The table reports test statistics, adjusted p-values, significance levels, and Vargha–Delaney A (VDA) effect sizes.

Microscale street element	**G1**	**G2**	n_1	n_2	**stat**	p	p_{adj}	**sig.**	**VDA**
Wide sidewalk	MI	OA	30	30	0.628	0.53	1	ns	0.456
Wide sidewalk	MI	SR	30	30	-0.004	0.997	1	ns	0.506
Wide sidewalk	MI	VI	30	30	2.832	0.005	0.027	*	0.302
Wide sidewalk	OA	SR	30	30	-0.632	0.528	1	ns	0.547
Wide sidewalk	OA	VI	30	30	2.205	0.027	0.11	ns	0.345
Wide sidewalk	SR	VI	30	30	2.837	0.005	0.027	*	0.316
Flat sidewalk	MI	OA	30	30	-0.002	0.998	1	ns	0.496
Flat sidewalk	MI	SR	30	30	0.286	0.775	1	ns	0.482
Flat sidewalk	MI	VI	30	30	3.727	0	0.001	**	0.252
Flat sidewalk	OA	SR	30	30	0.288	0.773	1	ns	0.487
Flat sidewalk	OA	VI	30	30	3.729	0	0.001	**	0.238
Flat sidewalk	SR	VI	30	30	3.441	0.001	0.002	**	0.275
Smooth sidewalk	MI	OA	30	30	0.42	0.675	0.993	ns	0.469
Smooth sidewalk	MI	SR	30	30	2.228	0.026	0.103	ns	0.351
Smooth sidewalk	MI	VI	30	30	2.909	0.004	0.022	*	0.301
Smooth sidewalk	OA	SR	30	30	1.809	0.07	0.211	ns	0.378
Smooth sidewalk	OA	VI	30	30	2.489	0.013	0.064	ns	0.327
Smooth sidewalk	SR	VI	30	30	0.68	0.496	0.993	ns	0.458
Separated pedestrian space	MI	OA	30	30	-2.115	0.034	0.172	ns	0.636
Separated pedestrian space	MI	SR	30	30	-1.418	0.156	0.469	ns	0.597
Separated pedestrian space	MI	VI	30	30	-3.197	0.001	0.008	**	0.731
Separated pedestrian space	OA	SR	30	30	0.697	0.486	0.558	ns	0.453
Separated pedestrian space	OA	VI	30	30	-1.083	0.279	0.558	ns	0.564
Separated pedestrian space	SR	VI	30	30	-1.779	0.075	0.301	ns	0.622
Lowered kerb	MI	OA	30	30	2.036	0.042	0.125	ns	0.349
Lowered kerb	MI	SR	30	30	1.469	0.142	0.284	ns	0.407
Lowered kerb	MI	VI	30	30	4.47	0	0	***	0.217
Lowered kerb	OA	SR	30	30	-0.567	0.571	0.571	ns	0.543
Lowered kerb	OA	VI	30	30	2.435	0.015	0.06	ns	0.317
Lowered kerb	SR	VI	30	30	3.001	0.003	0.013	*	0.311
Accessible signals at intersections	MI	OA	30	30	-0.2	0.841	1	ns	0.515
Accessible signals at intersections	MI	SR	30	30	0.669	0.503	1	ns	0.446
Accessible signals at intersections	MI	VI	30	30	-3.131	0.002	0.009	**	0.727
Accessible signals at intersections	OA	SR	30	30	0.87	0.384	1	ns	0.434
Accessible signals at intersections	OA	VI	30	30	-2.931	0.003	0.014	*	0.712
Accessible signals at intersections	SR	VI	30	30	-3.801	0	0.001	***	0.758
Places to rest	MI	OA	30	30	-2.4	0.016	0.082	ns	0.672
Places to rest	MI	SR	30	30	-0.73	0.466	0.931	ns	0.549
Places to rest	MI	VI	30	30	0.54	0.589	0.931	ns	0.462
Places to rest	OA	SR	30	30	1.671	0.095	0.379	ns	0.39
Places to rest	OA	VI	30	30	2.94	0.003	0.02	*	0.284
Places to rest	SR	VI	30	30	1.27	0.204	0.613	ns	0.416

B.5 Within-groups variation

This section presents the complete results of within-groups analyses, examining variation in perceived walking difficulty and facilitation across key characteristics. Differences are assessed by mobility assistive device type and gender using Mann–Whitney U tests, and by age using Spearman's rank correlations.

Mobility assistive devices

Table B.5 presents the full results of the Mann–Whitney U tests comparing perceived walking difficulty and facilitation between manual and powered wheelchair users within the mobility-impaired group, complementing the findings reported in the main text.

Table B.5: Mann–Whitney U test statistics (W), p-values, effect sizes (r), and effect size classifications comparing perceived walking difficulty and facilitation associated with microscale sidewalk and crossing elements between manual wheelchair users and powered wheelchair users.

Microscale street elements	**W**	**p-value**	**r**	**Effect size label**
Cross-slope	90.5	0.492	0.138	small
Crossing surface problem	111	0.045	0.4	medium
High kerbs	40.5	0.024	0.451	medium
Lack of rest places	98	0.179	0.269	small
Lack of street lights	104.5	0.135	0.299	small
Long crossing	97	0.286	0.213	small
Large-scale obstacles	62	0.375	0.177	small
Sidewalk material type	84	0.752	0.063	negligible
Missing sidewalk	100	0.227	0.241	small
Narrow sidewalk	79.5	0.955	0.011	negligible
No accessible signals at intersections	106.5	0.091	0.338	medium
No zebra crossing	93	0.403	0.167	small
Faded zebra crossing markings	71	0.612	0.101	small
Shared spaces	114.5	0.037	0.417	medium
Small-scale obstacles	50	0.122	0.31	medium
Stairs	72	0.378	0.176	small
Steep sidewalk	108.5	0.095	0.333	medium
Tram tracks at crossing	124	0.008	0.529	large
Uneven sidewalk	73.5	0.813	0.047	negligible
Accessible pedestrian signals at intersection	88.5	0.568	0.114	small
Flat sidewalk	56.5	0.145	0.292	small
Lowered kerbs	90	0.183	0.266	small
Places to rest	86.5	0.629	0.097	negligible
Separated space	62	0.349	0.187	small
Smooth sidewalk	70	0.600	0.105	small
Adequate street lighting	68	0.572	0.113	small
Wide sidewalk	67.5	0.517	0.129	small
Zebra crossing	74	0.835	0.042	negligible

Gender

Table B.6 presents the full results of the Mann–Whitney U tests comparing perceived walking difficulty and facilitation between male and female participants across all four population groups, complementing the findings reported in the main text.

Table B.6: Mann–Whitney U test statistics (W), p-values, effect sizes (r), and corresponding effect size classifications for differences in perceived walking difficulty and facilitation associated with microscale sidewalk and crossing elements among mobility-impaired individuals, mobility-restricted adults aged 65 years and older, situationally restricted individuals, and visually impaired individuals.

Microscale street elements	W	p.value	r	Effect size label
Mobility impaired individuals				
Narrow sidewalk	80	0.817	0.045	negligible
Steep sidewalk	66.5	0.356	0.178	small
Cross-slope	68.5	0.402	0.161	small
Small-scale obstacle	85.5	1.000	0	negligible
Large-scale obstacle	82	0.897	0.025	negligible
Stairs	72	0.354	0.178	small
Sidewalk material type	60.5	0.207	0.243	small
Uneven sidewalk	70.5	0.453	0.145	small
High kerb	87.5	0.913	0.021	negligible
No zebra crossing	100.5	0.429	0.152	small
No accessible signals at intersection	69	0.405	0.16	small
Tram tracks at crossing	83	0.937	0.015	negligible
Long crossing	69	0.410	0.158	small
Crossing surface problems	47.5	0.047	0.382	medium
Faded zebra crossing markings	70	0.316	0.193	small
Shared pedestrian space	102	0.384	0.167	small
Lack of places to rest	63	0.180	0.258	small
Missing sidewalk	89	0.856	0.035	negligible
Lack of street lighting	96.5	0.561	0.112	small
Wide sidewalk	75	0.575	0.108	small
Flat sidewalk	65	0.253	0.22	small
Smooth sidewalk	67.5	0.316	0.193	small
Separated pedestrian space	61	0.197	0.248	small
Lowered kerb	79	0.655	0.086	negligible
Zebra crossing	52	0.067	0.353	medium
Accessible pedestrian signals at intersection	71	0.477	0.137	small
Places to rest	89	0.849	0.037	negligible
Adequate street lighting	69	0.399	0.162	small
Mobility restricted individuals above 65 years old				
Narrow sidewalk	110.5	0.642	0.085	negligible
Steep sidewalk	123	0.294	0.192	small
Cross-slope	141	0.058	0.346	medium
Small-scale obstacle	121	0.336	0.176	small
Large-scale obstacle	120	0.370	0.164	small
Stairs	107	0.765	0.055	negligible
Sidewalk material type	141	0.016	0.44	medium
Uneven sidewalk	116.5	0.459	0.135	small
High kerb	93	0.901	0.023	negligible
No zebra crossing	143	0.050	0.358	medium
No accessible signals at intersection	131.5	0.149	0.264	small
Tram tracks at crossing	136	0.098	0.302	medium
Long crossing	164	0.003	0.534	large
Crossing surface problems	130.5	0.143	0.267	small
Faded zebra crossing markings	116	0.453	0.137	small
Shared pedestrian space	116.5	0.319	0.182	small
Lack of places to rest	123.5	0.259	0.206	small
Missing sidewalk	122	0.329	0.178	small
Lack of street lighting	116	0.329	0.178	small
Wide sidewalk	92	0.714	0.067	negligible
Flat sidewalk	77	0.240	0.215	small
Smooth sidewalk	84	0.430	0.144	small
Separated pedestrian space	91.5	0.695	0.072	negligible

Microscale street elements	W	p.value	r	Effect size label
Lowered kerb	109.5	0.658	0.081	negligible
Zebra crossing	125	0.238	0.216	small
Accessible pedestrian signals at intersection	111.5	0.613	0.092	negligible
Places to rest	65	0.109	0.292	small
Adequate street lighting	77	0.298	0.19	small
Situationally restricted individuals				
Narrow sidewalk	92.5	0.740	0.063	negligible
Steep sidewalk	101	0.434	0.148	small
Cross-slope	109	0.237	0.223	small
Small-scale obstacle	104.5	0.337	0.182	small
Large-scale obstacle	86.5	0.979	0.005	negligible
Stairs	135.5	0.012	0.476	medium
Sidewalk material type	121	0.057	0.36	medium
Uneven sidewalk	104.5	0.337	0.182	small
High kerb	130.5	0.022	0.434	medium
No zebra crossing	114.5	0.136	0.282	small
No accessible signals at intersection	118.5	0.074	0.337	medium
Tram tracks at crossing	119	0.057	0.36	medium
Long crossing	123	0.037	0.394	medium
Crossing surface problems	132	0.015	0.458	medium
Faded zebra crossing markings	95	0.507	0.125	small
Shared pedestrian space	107	0.274	0.207	small
Lack of places to rest	97.5	0.476	0.135	small
Missing sidewalk	118.5	0.094	0.316	medium
Lack of street lighting	99	0.463	0.139	small
Wide sidewalk	71	0.417	0.153	small
Flat sidewalk	18.5	0.000	0.712	large
Smooth sidewalk	17.5	0.000	0.671	large
Separated pedestrian space	83	0.916	0.02	negligible
Lowered kerb	36	0.005	0.534	large
Zebra crossing	45.5	0.035	0.397	medium
Accessible pedestrian signals at intersection	71.5	0.489	0.131	small
Places to rest	51.5	0.086	0.324	medium
Adequate street lighting	68	0.378	0.167	small
Visually impaired individuals				
Narrow sidewalk	90	0.848	0.035	negligible
Steep sidewalk	85	0.633	0.087	negligible
Cross-slope	105.5	0.615	0.092	negligible
Small-scale obstacle	126	0.119	0.284	small
Large-scale obstacle	124.5	0.160	0.257	small
Stairs	97.5	0.905	0.022	negligible
Sidewalk material type	107	0.564	0.105	small
Uneven sidewalk	118	0.267	0.203	small
High kerb	90	0.849	0.035	negligible
No zebra crossing	115	0.350	0.171	small
No accessible signals at intersection	106	0.597	0.097	negligible
Tram tracks at crossing	107.5	0.550	0.109	small
Long crossing	83.5	0.624	0.09	negligible
Crossing surface problems	106.5	0.573	0.103	small
Faded zebra crossing markings	107.5	0.546	0.11	small
Shared pedestrian space	106	0.596	0.097	negligible
Lack of places to rest	84.5	0.578	0.102	small
Missing sidewalk	138.5	0.041	0.374	medium
Lack of street lighting	76.5	0.416	0.149	small
Wide sidewalk	89	0.813	0.043	negligible
Flat sidewalk	82.5	0.584	0.1	small
Smooth sidewalk	66.5	0.179	0.245	small
Separated pedestrian space	115	0.283	0.196	small
Lowered kerb	75	0.369	0.164	small
Zebra crossing	98.5	0.862	0.032	negligible
Accessible pedestrian signals at intersection	69	0.125	0.28	small
Places to rest	98	0.878	0.028	negligible
Adequate street lighting	117	0.279	0.198	small

Age

Table B.7 presents the results of the Spearman rank correlation analysis examining the relationship between age and perceived walking difficulty and facilitation across microscale street elements within each population group, complementing the summary findings reported in the main text.

Table B.7: Spearman's rank correlation coefficients (ρ) and associated p-values between microscale sidewalk and crossing elements and perceived walking difficulty among mobility-impaired individuals, mobility-restricted adults aged 65 years and older, situationally restricted individuals, and visually impaired individuals.

Microscale street element	ρ	**p-value**
Mobility impaired individuals		
Cross-slope	0.185	0.327
Crossing surface problems	0.0842	0.658
High kerb	-0.0817	0.668
Lack of places to rest	0.0604	0.751
Lack of street lighting	-0.0172	0.928
Long crossing	0.0233	0.903
Large-scale obstacle	-0.213	0.258
Sidewalk material type	0.224	0.234
Missing sidewalk	-0.197	0.297
Narrow sidewalk	-0.192	0.308
No accessible signals at intersection	0.101	0.594
No zebra crossing	-0.0976	0.608
Faded zebra crossing markings	0.0422	0.825
Shared pedestrian space	0.109	0.568
Small-scale obstacle	0.0691	0.717
Stairs	-0.355	0.0546
Steep sidewalk	0.355	0.0546
Tram tracks at crossing	0.0133	0.944
Uneven sidewalk	0.257	0.171
Accessible signals at intersection	-0.306	0.1
Flat sidewalk	0.134	0.48
Lowered kerb	0.1	0.597
Places to rest	-0.203	0.282
Separated pedestrian space	-0.371	0.0433
Smooth sidewalk	0.0824	0.665
Adequate street lighting	-0.273	0.145
Wide sidewalk	0.0884	0.642
Zebra crossing	-0.0583	0.76
Mobility restricted individuals above 65 years old		
Cross-slope	-0.102	0.59
Crossing surface problems	0.0178	0.925
High kerb	-0.316	0.102
Lack of places to rest	0.205	0.277
Lack of street lighting	-0.00449	0.982
Long crossing	0.0455	0.811
Large-scale obstacle	-0.0909	0.633
Sidewalk material type	0.0936	0.629
Missing sidewalk	0.0769	0.686
Narrow sidewalk	-0.168	0.374
No accessible signals at intersection	0.136	0.474
No zebra crossing	-0.104	0.585
Faded zebra crossing markings	0.00934	0.961
Shared pedestrian space	-0.00256	0.989
Small-scale obstacle	-0.161	0.395
Stairs	-0.286	0.126
Steep sidewalk	-0.242	0.198
Tram tracks at crossing	0.0747	0.695
Uneven sidewalk	-0.0576	0.762
Accessible signals at intersection	-0.0633	0.74
Flat sidewalk	-0.198	0.295
Lowered kerb	-0.0209	0.913
Places to rest	-0.379	0.0387
Separated pedestrian space	-0.0592	0.756

Microscale street element	ρ	**p-value**
Smooth sidewalk	-0.173	0.362
Adequate street lighting	-0.353	0.0555
Wide sidewalk	0.0267	0.889
Zebra crossing	-0.0886	0.642
Situationally restricted individuals		
Cross-slope	0.128	0.501
Crossing surface problems	0.381	0.0377
High kerb	0.279	0.135
Lack of places to rest	0.243	0.196
Lack of street lighting	0.337	0.0684
Long crossing	0.26	0.165
Large-scale obstacle	0.163	0.388
Sidewalk material type	0.414	0.023
Missing sidewalk	0.192	0.308
Narrow sidewalk	0.00823	0.966
No accessible signals at intersection	0.31	0.0951
No zebra crossing	0.289	0.121
Faded zebra crossing markings	0.42	0.0207
Shared pedestrian space	0.342	0.0646
Small-scale obstacle	0.336	0.0695
Stairs	0.0932	0.624
Steep sidewalk	-0.095	0.618
Tram tracks at crossing	0.431	0.0173
Uneven sidewalk	0.386	0.035
Accessible signals at intersection	0.0364	0.849
Flat sidewalk	0.0384	0.84
Lowered kerb	-0.331	0.0737
Places to rest	0.103	0.587
Separated pedestrian space	-0.123	0.518
Smooth sidewalk	0.0258	0.892
Adequate street lighting	-0.138	0.466
Wide sidewalk	-0.000392	0.998
Zebra crossing	-0.0103	0.957
Visually impaired individuals		
Cross-slope	0.334	0.0663
Crossing surface problems	0.308	0.0918
High kerb	0.291	0.112
Lack of places to rest	0.31	0.0895
Lack of street lighting	0.288	0.116
Long crossing	0.108	0.562
Large-scale obstacle	-0.0348	0.853
Sidewalk material type	0.321	0.0788
Missing sidewalk	0.0522	0.78
Narrow sidewalk	0.147	0.43
No accessible signals at intersection	-0.188	0.31
No zebra crossing	-0.365	0.0433
Faded zebra crossing markings	-0.0919	0.623
Shared pedestrian space	-0.158	0.395
Small-scale obstacle	-0.0488	0.794
Stairs	0.0804	0.667
Steep sidewalk	0.272	0.139
Tram tracks at crossing	-0.0602	0.748
Uneven sidewalk	0.203	0.272
Accessible signals at intersection	0.319	0.0804
Flat sidewalk	-0.258	0.161
Lowered kerb	-0.0513	0.784
Places to rest	-0.122	0.512
Separated pedestrian space	0.0666	0.722
Smooth sidewalk	-0.0508	0.786
Adequate street lighting	-0.181	0.33
Wide sidewalk	-0.213	0.25
Zebra crossing	0.111	0.554

Appendix C

Supplementary Material for Chapter 4: Developing enriched pedestrian networks with accessibility information

C.1 Description of accessibility features and tags

Table C.1: Description of all the accessibility feature types and their associated tags from the ZüriACT dataset.

Feature type	Category	Description	Tags
Sidewalk	Obstacle in path	Objects that block the pedestrian path	pole, tree, vegetation, trash/recycling can, parked car, parked bike, construction, sign, stairs, height difference (step), narrow, litter/-garbage, parked scooter/motorcycle, outdoor dining area
	Surface problem	A problem or damage in the sidewalk's surface; can also be caused by the material used to pave the sidewalk with	bumpy, cracks, grass, narrow, construction, brick/cobblestone, uneven/slated, very broken, height difference (step), rail/tram track, sand/gravel, utility panel
	Missing sidewalk	–	ends abruptly, street has a sidewalk, street has no sidewalk, shared pedestrian/car space
Intersection	Kerb ramp	A sloped surface built into a kerb or sidewalk to provide a smooth transition between the sidewalk and the street	narrow, missing tactile, steep, not enough landing space, not level with street, surface problem, pooled water, points into traffic
	Missing kerb ramp	–	–
	Crosswalk	A defined area to cross the road	paint fading, broken surface, uneven surface, brick/cobblestone, bumpy, rail/tram track, no pedestrian priority, very long crossing
	Signal	Pedestrian traffic lights for crossing the road or devices that provide auditory, visual, and vibrotactile information to pedestrians	has button, button waist height

C.2 Description of accessibility features reclassification

Table C.2: Reclassification of original ZüriACT labels into new label types based on associated tags.

Original ZüriACT labels	**Reclassified labels**	**Tags**
Obstacle in path	Small-scale obstacles	pole, vegetation, sign, trash/recycling can, fire hydrant, parked bike, parked scooter/motorcycle, litter/garbage, bollard
	Large-scale obstacles	tree, outdoor dining area, construction, parked car, garage entrance
	Steps / Stairs	height difference, stairs
Surface problem	Surface condition	bumpy, cracks, uneven/slanted, very broken, rail/tram track
	Surface material type	brick/cobblestone, sand/gravel, grass
	Small-scale obstacles	utility panel
	Large-scale obstacles	construction
	Steps / Stairs	height difference
Crosswalk	Unmarked crosswalk	no pedestrian priority
	Crosswalk	paint fading, broken surface, uneven surface, brick/cobblestone, bumpy, rail/tram track, very long crossing
Missing sidewalk	Shared space	shared pedestrian/car space
	No sidewalk	street has no sidewalk, street has a sidewalk, gravel/dirt road, ends abruptly, covered walkway
Kerb ramps	–	–
Missing kerb ramp	–	–
Pedestrian signal	–	–

Appendix D

Supplementary Material for Chapter 5: Impact of microscale street elements on accessibility disparities

D.1 Distribution of accessibility features

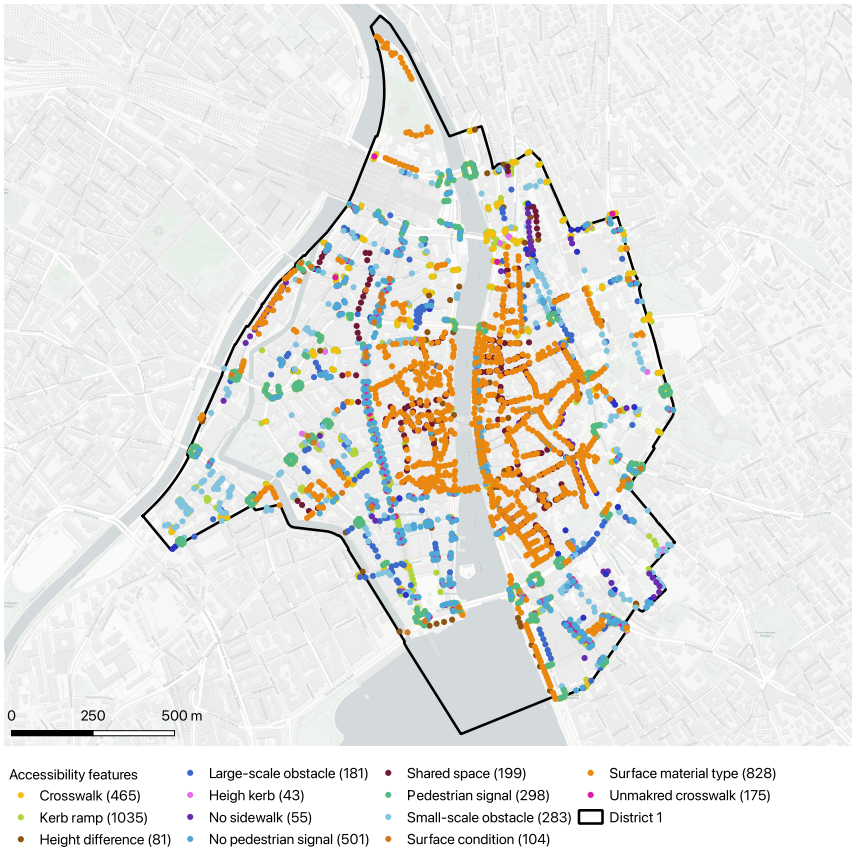


Figure D.1: Types of accessibility features and the number of features from each type included in the final dataset after clustering.

Declaration of the usage of AI

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

During the preparation of this work, I used AI tools such as ChatGPT (Version 5.3), developed by OpenAI, and Grammarly to polish the language and improve the clarity and grammar of the text where needed.

Bern, 20 April 2026



Alexandra Ioana Georgescu