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Developing enriched pedestrian networks using accessibility features

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Abstract. Accessibility studies often focus on the general population, overlooking individual differences in mobility capacities and the role of external factors. Microscale street elements such as stairs, high kerbs, and sidewalk cracks can significantly impact urban mobility for individuals with restricted movement capacities. 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. Using this network, we evaluate each segment by computing an impedance score to quantify accessibility. Furthermore, we demonstrate how the network can be tailored to individual mobility needs and highlight its potential as a decision-making tool for urban planners and civil engineers to identify and prioritise targeted interventions for vulnerable populations.

Submission Type. Analysis

BoK Concepts. [AM11] Network analysis, [AM11-7] Accessibility modelling, [AM5-3] Spatial cluster analysis

Keywords. Spatial accessibility, Microscale elements, Mobility restriction, Pedestrian networks, Urban environment

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 Organisation, 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., 2016), 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., 2016), 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.

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 Tab. A1 in the Appendix 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 Zurich (2021), was utilized (Allahbakhshi & Harrafamoughin, 2025).

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.

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.

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. 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 generalized DBSCAN (GDBSCAN) method (Sander et al., 1998), as this can consider both spatial and non-spatial attributes (Fig. 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.

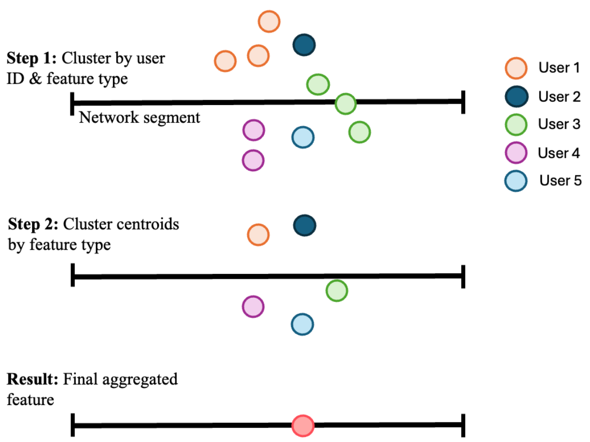

Figure 1. The two-step clustering process exemplified for a subset features of the same type. First, the features collected by the same user, illustrated by colour, are clustered together and the centroid of the cluster is kept. Second, all features of the same type that fall into the specific distance threshold are clustered together.

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 (Tab. 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 width smaller than 1 meter were considered impassable.

Table 1. Width and slope values are categorised into 5 severity levels.

Severity	Width (m)	Slope (%)
0	> 1.80	< 1
1	1.6 ≤ width < 1.8	1 ≤ slope < 2
2	1.4 ≤ width < 1.6	2 ≤ slope < 3
3	1.2 ≤ width < 1.4	3 ≤ slope < 4
4	1.0 ≤ width < 1.2	4 ≤ 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.

3.4 Data and Software Availability Section

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 can be provided upon request.

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 (Tab. 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 Tab. 2.

Table 2. Clustering results and eps choice for each feature type.

Feature Type		1st Clustering		2nd Clustering	
	No.	eps	No.	eps	No.
Kerb Ramp	2560	2	2141	3	1035
No Kerb Ramp	61	2	55	3	43
Pedestrian Signal	935	2	724	3	298
Crosswalk	1154	2	986	6	465
Height Difference	173	7	139	10	81
Large Scale Obstacle	266	7	236	8	181
Small Scale Obstacle	428	2	359	4	283
Surface Condition	163	5	148	5	104
Surface Material Type	2469	5	2063	7	828
No sidewalk	65	7	63	10	55
Sidewalk ends abruptly	33	7	31	10	26
Shared Space	306	7	262	10	199

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. Fig. 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 Fig. 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,

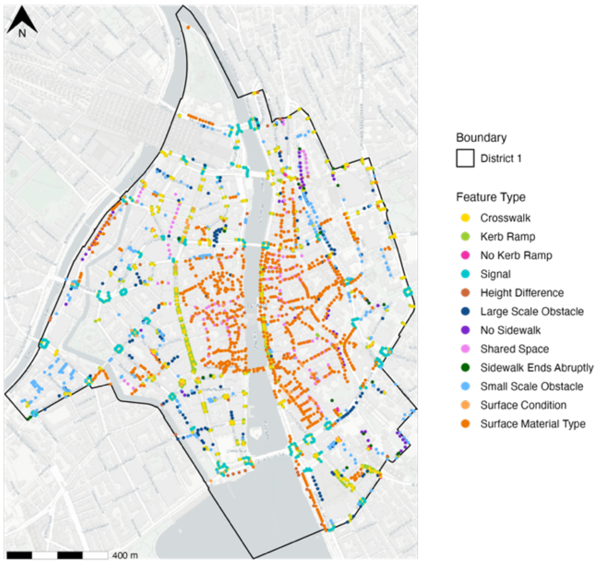

Figure 2. Overview of the distribution of accessibility features in the study area.

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 Fig. 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.

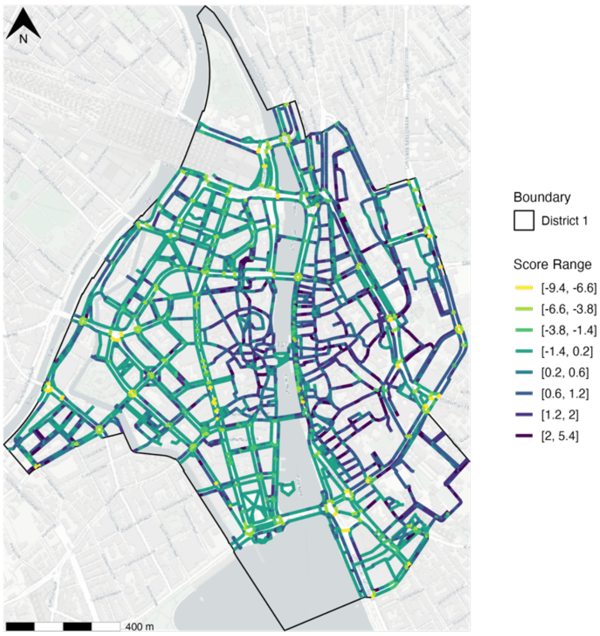

Figure 3. The enriched pedestrian network, segments are coloured by their impedance score, for the profile of a wheelchair user. Score range divided using natural breaks.

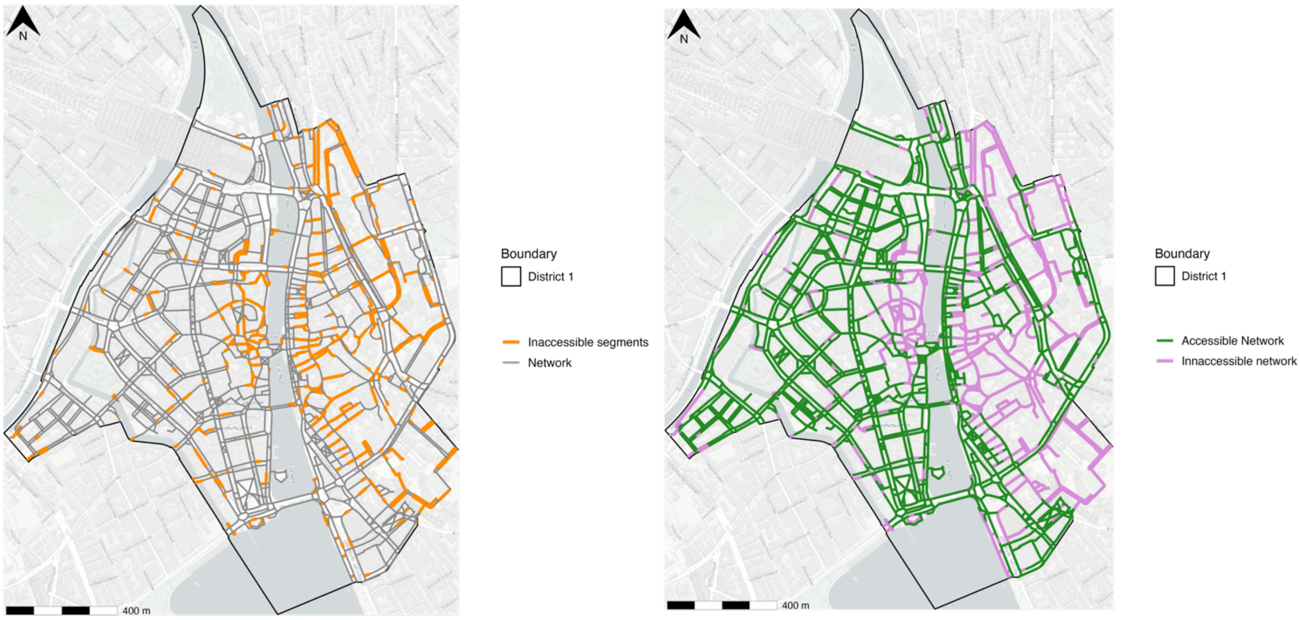

Figure 4. Overview of the distribution of inaccessible segments (left) and the connected accessible network left as a consequence of these segments (right).

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 Fig. 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.

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.

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.

Declaration of Generative AI in writing

The authors declare that they have used Generative AI tools in the preparation of this manuscript. Specifically, the AI tools were utilized for language editing and sentence structure but not for generating scientific content, research data, or substantive conclusions. All intellectual and creative work, including the analysis and interpretation of data, is original and has been conducted by the authors without AI assistance.

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Appendix

Table A1. Description of all the accessibility feature types and their associated tags from the ZüriACT dataset.

	Feature type	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/grovel, 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