AGILE: GIScience Series, 7, 12, 2026. https://doi.org/10.5194/agile-giss-7-12-2026
Proceedings of the 29th AGILE Conference on Geographic Information Science, 16–19 June 2026.
Eds.: Evelyn Uuemaa, Alexander Kmoch, Holger Virro, and Simon Scheider
This contribution underwent peer review based on a full paper submission.

OpenStreetMap Suitability Analysis for Wheelchair Routing

Ivan Majic [1], Thomas Gegenleithner[1], and Johannes Scholz [2]

[1]Working Group Geoinformation, Institute of Geodesy, Graz University of Technology, Graz, Austria
[2]Department of Geoinformatics—Z GIS, University of Salzburg, Salzburg, Austria

Correspondence: Ivan Majic (majic@tugraz.at)

Abstract. Navigation and wayfinding are essential for modern mobility and are readily available for vehicles and pedestrians. However, the process can be more challenging for wheelchair users, as the availability of suitable services may be limited. This study investigates the suitability of OpenStreetMap (OSM) for wheelchair navigation. The primary goal is to identify OSM tags (i.e., key-value combinations) that are particularly relevant for wheelchair users. Previous research has shown that the street type, surface, gradient, and barriers are particularly challenging factors for wheelchair navigation and are therefore analyzed in more detail here. Particular emphasis is placed on analyzing pavement conditions and the related challenges in urban infrastructure. Additionally, an area of interest in the city of Graz is selected for a detailed analysis and case study. Another aspect of this work focuses on generating a network specifically for wheelchair users using open-source data and tools. This study highlights the distinctions between pedestrian and wheelchair navigation and demonstrates this quantitatively by comparing their respective routes for numerous origin-destination pairs. Additionally, a performance evaluation is conducted on the established wheelchair network.

Submission Type. Full Paper

BoK Concepts. [AM11-7] Accessibility modeling, [AM11-3] Least-cost shortest path, [GS4-3b] Citizens and volunteered geographic information

Keywords. Suitability Analysis, Wheelchair, Routing, OpenStreetMap, Accessibility, DEM, Slope

1 Introduction

Routing applications and navigation services are used daily in professional life and leisure activities. While motorists, cyclists, and pedestrians can easily find the best route between two places, this is more difficult for wheelchair users. Navigating unfamiliar areas poses significant challenges for wheelchair users when relying on traditional routing applications and navigation services designed for pedestrians and cyclists. These services often fail to consider accessibility features, leading wheelchair users to encounter barriers like stairs and other obstacles, which can make certain routes insurmountable. In addition, wheelchair users may face longer routes or be forced to backtrack if the path suggested to them is incorrect and proves to be inaccessible due to unforeseen obstacles. This can add extra time and effort to their journey.

To address the lack of route mapping services for wheelchair users, more research is needed. This paper examines how routing applications can help make daily life easier for wheelchair users.

This work examines the potential of OSM for wheelchair routing. However, how suitable are OSM data for the implementation of wheelchair routing? To address this question, we will assess OSM's utility using routing algorithms. We assume that wheelchair routing can be considered as pedestrian routing with additional obstacles. Taking into account factors such as gradient, steps, sidewalk condition, and pedestrian traffic, we hypothesize that OSM can be used for wheelchair routing in a similar way to pedestrian routing. To test and evaluate this hypothesis, we will address four major research questions:

1. What tags in OSM are important for wheelchair routing?
2. How does wheelchair routing differ from pedestrian routing?
3. How can OSM be used and optimized for wheelchair routing?
4. How suitable is the wheelchair routing in Graz compared to other cities in Austria?

Thus, the contributions of this study are (a) the systematic integration of OSM and elevation data for improved slope calculation and consideration in wheelchair routing, (b) systematic review, identification, and computational implementation of the wheelchair users' mobility and routing requirements, and (c) empirical local validation of the proposed wheelchair routing methodology in three Austrian cities.

The paper is structured as follows: Section 2 introduces previously conducted research and various relevant projects. Section 3 discusses the needs and abilities of wheelchair users in the context of current regulations and stipulations. The methodology in Section 4 presents the available data and software and then focuses on tag analysis for wheelchair routing. In Section 5, three distinct experimental tests are conducted to analyze the navigational capabilities of the custom-created routing network. Section 6 compares three cities based on their navigational capabilities, primarily relying on a comparison of various OSM tags. Section 7 synthesizes and discusses the findings from the preceding sections, addressing the major outcomes.

2 Related Work

The use of routing applications has seen a significant increase in the last two decades, with web-map services gaining significant utility in daily life. Considerable research efforts have been dedicated to this topic, including various studies based on OSM.

As an early analysis of OSM data, Haklay (2010) compared it with Great Britain's national mapping agency and found it to be fairly accurate. Neis et al. (2011) further assessed VGI road data and showed that in well-developed regions, OSM quality approaches that of commercial datasets in both temporal and geometric accuracy.

For vehicle navigation, Graser et al. (2015) evaluated OSM for routing in Vienna, comparing road network characteristics and route geometries. Their results indicate that OSM can serve as a reliable and cost-effective alternative to proprietary datasets, though concerns remain regarding vandalism and regional inconsistencies—issues also observed in this study.

Pedestrian-focused research, such as Andreev et al. (2015), highlights challenges that are also relevant to wheelchair routing, including missing sidewalk detail and limited support for plazas and parks. They propose generating sidewalks and additional edges to improve pedestrian routing. Zipf et al. (2016) and Novack et al. (2018) explore alternative routing concepts, emphasizing landmarks and user-preferred factors such as greenness or quietness, and integrating these into OSM-based routing systems. Lugtigheid et al. (2024) propose a sidewalk-based routing system where users can create their own accessibility profiles to receive custom tailored routes that are safer and more accessible for them. They also emphasize cases where sidewalk-based routing can detect suitable routes that are overlooked when routing is performed on a street-level.

Several studies address navigation for people with mobility impairments. Early work by Matthews et al. (2003) and Beale et al. (2006) modeled wheelchair accessibility using GIS, considering surface types and obstacles, though not based on OSM. Ding et al. (2007) introduced real-time, dynamic routing for wheelchair users. Using OSM, Neis and Zielstra (2014) examined required parameters for disability-oriented routing and compared sidewalk completeness across cities, concluding that OSM sidewalk data is often insufficient. Tools such as *OSMatrix*[1] and *AccessMap*[2] further support quality assessment and walkway analysis.

A comparison of pedestrian and wheelchair routing by Tannert and Schöning (2018) shows that wheelchair routes are typically much longer. A collaborative study by Barczyszyn et al. (2018) developed a sidewalk-based routing model refined through user feedback. *WheelShare* (Edinger et al., 2019) focuses on optimal surface conditions, while Gharebaghi et al. (2021) propose a fuzzy, user-specific routing model. For electric wheelchairs, Dzafic et al. (2020) present *eNav*, which identifies energy-efficient routes and highlights the impact of poorly maintained infrastructure on accessibility. More recently, Hossain et al. (2025) introduced the MyPath system - a hybrid framework combining crowdsourced data with a sophisticated algorithmic analysis. This mobile application classifies streets based on user-contributed information about stairs, slopes, construction, and facilities, as well as vibration data from smartphone sensors. It also performes automated slope estimation based on data from OSM and Google's Elevation API to deliver personalized accessible routing recommendations.

2.1 Related Projects

Navigation for users without mobility impairments is supported by numerous routing applications, including commercial services such as *Google Maps*[3], *Waze*[4], *HERE WeGo*[5], and *Apple Maps*[6], as well as VGI-based systems like *OSRM*[7], *Valhalla*[8], and *Graphhopper*[9]. However, these services generally do not meet the specific requirements of wheelchair users. Notable initiatives addressing this gap include *wheelmap.org* by SOZIALHELDEN e.V.[10], and HeiGIT's *openrouteservice.org*, which allows users to select criteria such as maximum gradient or surface type. *AccessMap*[11],

---

[1] https://hex.ohsome.org

[2] https://www.accessmap.io

[3] https://www.google.com/maps

[4] https://www.waze.com/live-map/

[5] https://wego.here.com/

[6] https://www.apple.com/maps/

[7] https://project-osrm.org/

[8] https://github.com/valhalla/valhalla

[9] https://www.graphhopper.com/

[10] https://sozialhelden.de/

[11] https://www.accessmap.app/

developed at the University of Washington, offers routing adapted to different mobility needs for selected U.S. cities, incorporating gradient limits and barrier avoidance.

Additional open-source tools such as *routino*[12] and *opentripplanner*[13] also support wheelchair routing, and both rely on OSM data. In Austria, *wheelroute.at* uses OSM and *OSRM* and provides several wheelchair-specific routing profiles, including classic, electric, and sports wheelchairs.

3 Needs and abilities of wheelchair users

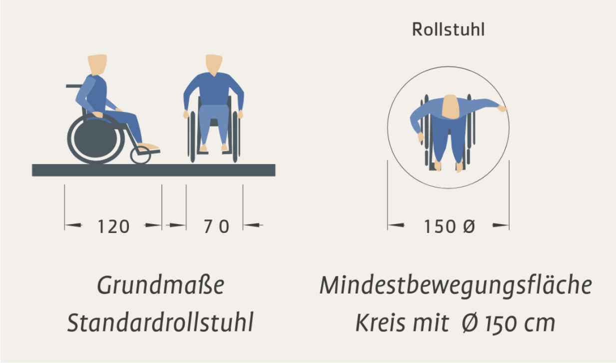
Wheelchairs are a valuable mode of transportation for people unable to walk due to physical impairment. To meet the individual needs of different users, wheelchairs are available in various configurations. Even though wheelchair standards are precisely defined by International Organization for Standardization's Technical Committee 173 for assistive products – subcommittee 1 for wheelchairs International Organization for Standardization, classifying wheelchairs is challenging due to their vast variety (National Academies of Sciences, Engineering, and Medicine, 2017). For this paper, wheelchairs are divided into two groups:

- Manual Wheelchair
- Electric-powered Wheelchair

Manual wheelchairs are generally lighter and more economical to acquire than electric wheelchairs. In the further course of this work, all research and testing will be conducted exclusively with manual wheelchairs lacking electric support. The research and testing focus specifically on the region of Austria, particularly the city of Graz, in compliance with the current regulations in effect in this area.

People with disabilities usually have a more challenging time in everyday life. In particular, access to publicly available services is often limited. The Federal Disability Equality Act (Bundeskanzleramt der Republik Österreich, 2026) has been in force in Austria since January 1, 2006. This law aims to make buildings and means of transport accessible and usable for people with disabilities in general without particular difficulties and outside help. The planning principles are laid down in the ÖNORM B 1600 (Standards, 2023). In most cases, construction barriers are not erected intentionally but result from a lack of expertise (Koch-Schmuckerschlag and Kalamidas, 2006).

For wheelchair navigation, requirements for paths and walkways are of particular importance. The path width must be at least 150 cm, and the passage width must not be less than 90 cm in the case of punctual obstacles. The longitudinal gradient should not exceed a maximum value of 6%, and a handrail should be installed for a gradient of more than 10%. Likewise, the cross slope of paths should have a maximum value of 2% but a target value of 0%. The road surface should be non-slip and rollable. Obstacles should be marked and mapped out. Steps and thresholds in the course of sidewalks are to be avoided. Ramps are to be constructed to overcome height differences. These should be straight and at least 120 cm wide, preferably 150 cm wide. Here, a maximum longitudinal gradient of 6% should not be exceeded, and a transverse gradient of 0% is a prerequisite too. If the ramp slope is greater than 4%, intermediate platforms must be provided after every 10 m for resting (Koch-Schmuckerschlag and Kalamidas, 2006). The most important requirements are summarized in Table 1.



(a) Basic dimensions standard wheelchair

(b) Narrow spaces for sidewalks

Figure 1. Wheelchair Requirements (source: Stadtbaudirektion Graz (Koch-Schmuckerschlag and Kalamidas, 2006))

4 Methodology

4.1 Data and Software availability

This study is carried out solely using freely and publicly available datasets and free and open-source software. The software repository containing pre-processed data and

---

[12] https://www.routino.org/

[13] https://www.opentripplanner.org/

Table 1. Summary Requirements for wheelchair navigation

Requirement	Unit	Annotation
Path width	150 [cm]	-
Path width	90 [cm]	for punctual obstacles
Longitudinal gradient	$\leq 6\%$	handrail if gradient $\geq$ 10 %
Cross slope	$\leq 2\%$	22%
Ramp width	120 [cm]	preferably 150 [cm] %
Ramp longitudinal slope	$\leq 6\%$	-
Ramp transverse slope	0%	-

code used to obtain the results of this study is available online with DOI 10.6084/m9.figshare.31333180[14].

The main dataset for the analysis of the street network and accessibility obstacles is the OpenStreetMap (OSM). (OSM) [15] is a free, editable map of the world that is built by volunteers and thus also known as Volunteered Geographical Information (VGI) - a term coined by Goodchild (2007). In addition, openly available digital elevation model (DEM) data from GIS Steiermark[16] were used to calculate slope for the terrain and routes (see more details in Section 4.2.4).

An open-source *PostgreSQL* database was used to store and manage the obtained OSM data in this study. PostgreSQL extensions, which are also free and open-source software, were used to handle various specific tasks. The *PostGIS* spatial extension was used for storage and manipulation of geographic data, *pgRouting* extension was used for calculating shortest paths between origins and destinations, *postgis_raster* extension was used for storage and manipulation of raster data (i.e., DEM and slope), and the *hstore* extension was used for storage and processing of OSM tags - attribute information stored in *key=value* format.

Other helper command-line software were also use to streamline the importing and conversion of the OSM and DEM data into formats suitable for further analysis in the PostgreSQL database. Namely *osm2pgsql*[17] to import OSM data into a PostGIS database, *osm2pgrouting*[18] to import OSM data and build networks for routing analyses, and *raster2pgsql* [19] to import DEM into the database.

4.2 Tag Analysis for Wheelchair routing

The OSM contains various tags for roads and street infrastructure. These tags vary from region to region, resulting in a lack of consistency. Primary features for navigation are roads, which are classified with the key *highway*. They describe all types of roads and footpaths. In the following subsections, different criteria for wheelchair navigation are analyzed. The question that arises is *what distinguishes wheelchair navigation from pedestrian and vehicle navigation?* Therefore, the essential accessibility criteria are investigated. A starting point for this study is the analysis of proposed regulations and applicable standards (Koch-Schmuckerschlag and Kalamidas, 2006). Other studies in the field of wheelchair navigation are also analyzed to find the most frequently mentioned factors (Gharebaghi et al., 2021; Kirschbaum et al., 2001; Beale et al., 2006; Ding et al., 2007).

Accordingly, the main attributes of wheelchair navigation result in: type of street, surface type, slope, width, smoothness, barriers, steps, and ramps.

In order to investigate these attributes in terms of their availability and applicability, a test area is defined. The urban area of Graz, the second largest city in the Republic of Austria with $307,912$ inhabitants and a total area of $127.58\,km^2$ Statistik Graz, is selected for this purpose. The OSM road network is cropped to the city borders and results in a total length of $2,947.42\,km$. Furthermore, a total of 92,231 elements are included in the OSM dataset.

To better understand essential keys, analyzing which combination appears the most is helpful. A chord diagram in Figure 2 visualizes the top 20 combinations of the OSM keys that most frequently occur in the area of interest. At first glance, it is apparent that the connections between *highway* and *surface*, as well as *highway* and *name* and *lit*, are particularly prominent.

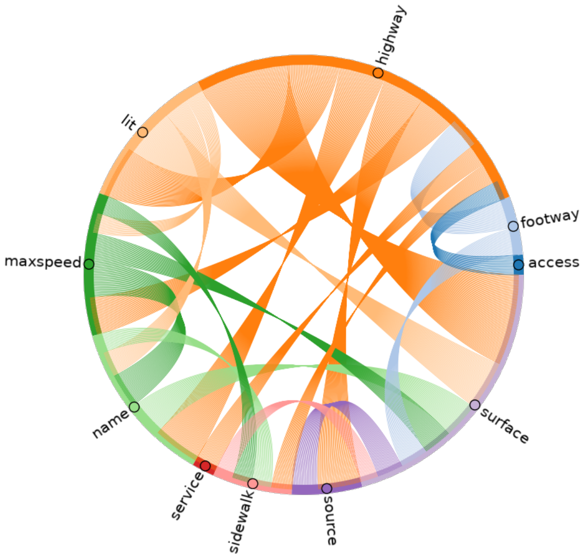


Figure 2. Chord Diagram Combinations of the Top 20 most common OSM tag keys used to describe road features in the study area.

---

[14] https://doi.org/10.6084/m9.figshare.31333180

[15] www.openstreetmap.org/

[16] https://gis.stmk.gv.at/atlas2/ogd_download.html

[17] https://osm2pgsql.org/

[18] osm2pgroutinghttps://github.com/pgRouting/osm2pgrouting

[19] https://postgis.net/docs/using_raster_dataman.html

In the ensuing subsections, various tags for navigation are examined and analyzed in depth. The analysis is limited to path-specific parameters. Properties such as light with the key *lit=** or destinations with key *maxspeed=** or *oneway* are not discussed.

4.2.1 Highway

Ways, roads, or paths are tagged with the key *highway* in OSM. It is essential to mention that the tag does not only refer to a highway in the sense of an American motorway. Roads differ in their classification and definition around the world. The official OSM wiki provides a comparison table for different road classifications of individual countries[20].

Overall, the key *highway* is among OSM's most common and frequently used tags. According to OSM's tag information webpage (https://taginfo.openstreetmap.org/keys/highway), it is the third most used key in OSM with 23.42%. In the defined test area, there are a total of 92,231 road sections over a length of 2,947.42 km. Figure 3 shows the relative proportion of the respective road type depending on the length. The three key-values *service*, *footway* and *residential* cover the most significant part of the road network with 73.99%. Roads with sidewalk information are of particular importance for wheelchair navigation. These are described in more detail in the next section.

Which types of roads can be used best for wheelchair navigation in OSM? Neis and Zielstra (2014) addressed this question in their work on route generation for disabled people, which helps identify the most important road types. Additionally, reviewing the requirements based on (Koch-Schmuckerschlag and Kalamidas, 2006) and consulting OSM's tag information webpage reveals that the essential highway types are: *living_street*, *pedestrian*, *residential*, *service*, *track*, *footway*, *cycleway*.

4.2.2 Sidewalks

Information about sidewalks is essential for individuals with limited mobility, as surface conditions, obstacles, and the presence or absence of pedestrian infrastructure critically influence route planning and accessibility. In OpenStreetMap (OSM), sidewalk information is represented through two principal approaches. First, roads tagged with *highway* may be supplemented by the attribute *sidewalk=*, indicating the existence of a sidewalk without mapping it as an independent geometry—an approach referred to as *refinement of the highway* OpenStreetMap Wiki. Second, sidewalks may be explicitly modeled as separate linear features using the combination *highway=footway* + *footway=sidewalk*. The former approach is slightly more prevalent in the study area with 12,904 elements (501.45 km), compared to 12,032 features (333.95 km) that are mapped with the latter approach. Figures 4a and 4b illustrate the spatial distribution of both tagging practices.

Despite ongoing efforts toward standardization, disagreement persists within the OSM community regarding the optimal representation of sidewalks. As outlined above, contributors either map sidewalks as independent footpath geometries or encode them as metadata on the adjacent road.

In terms of geometry, using *sidewalk=** limits network construction and prevents precise localization of sidewalk positions, which is particularly problematic at crossings. Crossing information stored only as a node at an intersection is often ambiguous and insufficient, especially for accessibility-relevant attributes such as kerb height or ramp details, which may apply to only one side of the road.

By contrast, the more recent method models crossings as linear features rather than nodes, enabling more accurate spatial representation and allowing intersection characteristics to be integrated into routing algorithms. Table 2 summarizes the differences between both approaches. Figure 5 illustrates them, with Figure 5a showing a crossing mapped via *sidewalk=** and Figure 5b depicting one mapped with *highway=footway* + *footway=sidewalk*.

This discussion has been addressed in more detail by a team from the Data Science for Social Good (DSSG) program sponsored by the University of Washington eScience Institute. The research of the team ended in a proposition for comprehensive mapping of pedestrian ways (as shown in Figure 5b) (Bolten et al., 2015).

The availability of detailed sidewalk parameters is essential for wheelchair navigation; however, such information remains incomplete or underrepresented in many cities (Mobasheri et al., 2017; Zipf et al., 2016). Recent initiatives have therefore focused on improving sidewalk completeness in crowdsourced maps. At the 2022 *State of the Map* conference[21], tools such as the QGIS plugin *Sidewalkreator* were presented to support automated sidewalk generation (Vestena et al., 2022). Additional research explores drone-based detection of sidewalks (Ferreira Olivatto et al., 2019) and machine-learning approaches (Gjeruldsen, 2020).

Estimating the total extent of the sidewalk network in the study area is complicated by heterogeneous tagging practices. To approximate network length, a baseline network using *highway=footway* + *footway=sidewalk* is constructed and subsequently merged with features tagged *sidewalk=**, excluding segments located within 15 m of an existing footway sidewalk to avoid over-representation.

The resulting dataset provides an improved, though still approximate, representation of the sidewalk network in

---

[20] https://wiki.openstreetmap.org/wiki/International_highway_classification_equivalence

[21] https://stateofthemap.org/

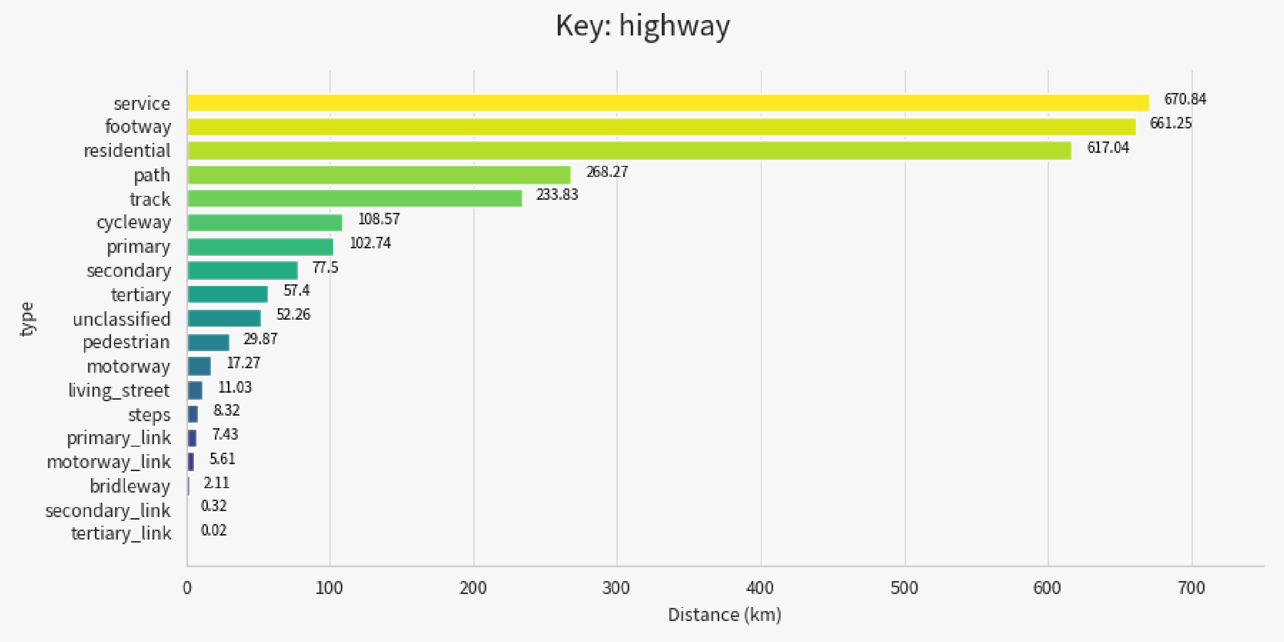
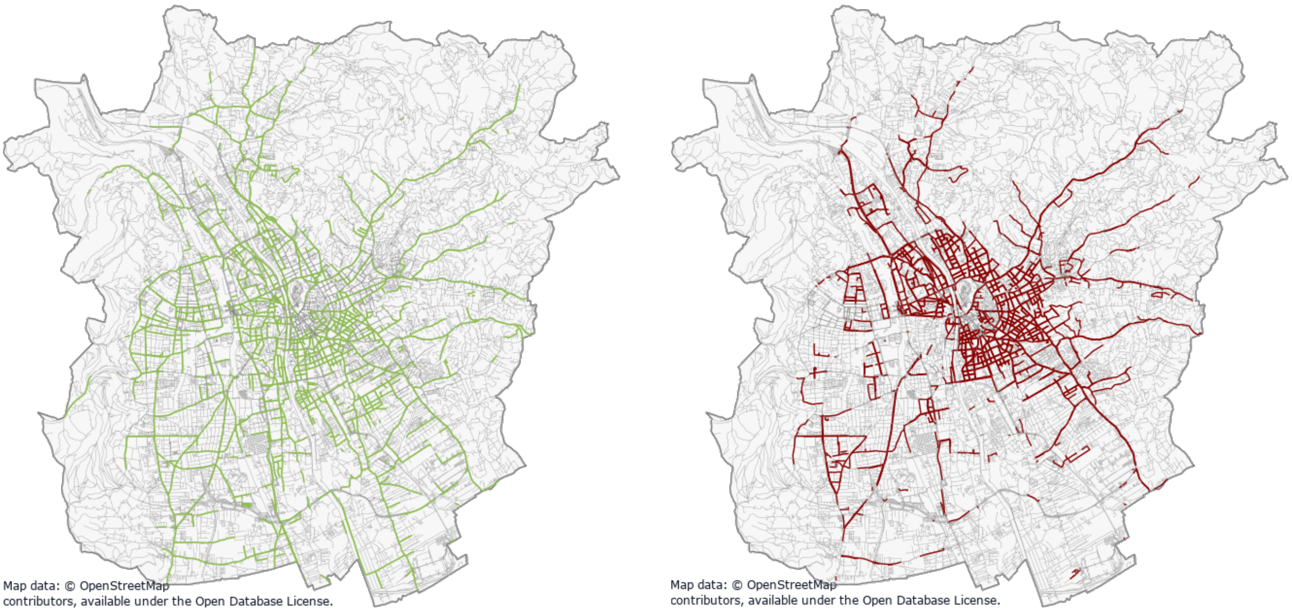


Figure 3. Types of roads (i.e., values of key *highway*) depending on the length.



(a) *sidewalk=**

(b) *highway=footway AND footway=sidewalk*

Figure 4. Overview of two different ways to describe sidewalks in OSM.

Graz. Small segments may be omitted due to the 15 m buffer, and inconsistencies in tagging—particularly cases where sidewalks are mapped only as *highway=footway* without *footway=sidewalk*—introduce further ambiguity regarding whether a feature represents a footway or a sidewalk.

4.2.3 Surface

Poor road and sidewalk surfaces pose significant challenges for people with disabilities. Surveys among wheelchair users consistently identify *gravel*, *grass*, *cobbles*, and uneven paving slabs as particularly problematic (Beale et al., 2006; Matthews et al., 2003). To assess these conditions in OSM, the key *surface* is examined. Within the Graz study area, 63.13% of the road network includes surface information, increasing to

Table 2. Comparison of two mapping approaches for sidewalks in the OSM

Approach	**sidewalk=***	**highway=fw + footway=sw**
Crossings geometry	nodes	lines connecting sidewalks
Curb information	merged into single point	separately described as nodes
Pedestrian islands	no spatial representation / only as metadata	spatial representation
Navigation	sidewalks as attributes of streets	standalone with sidewalks as way

(a) Crossing 1

(b) Crossing 2

Figure 5. Different Sidewalk Mapping Approaches for Crossings in OSM

94.27% for sidewalks mapped as *highway=footway* + *footway=sidewalk*. Figure 6 summarizes the distribution of the 12 most common surface types, with all categories below 2 km aggregated as *other*.

For wheelchair users, surface types such as *asphalt*, *paved*, *paving_stones*, *sett*, *cobblestone*, and *compacted* are particularly relevant. The tag *surface=paved* provides only a coarse description and, according to the OSM wiki[22], should be replaced with more specific values. In general, *surface=paving_stones* offers smoother conditions than *surface=sett* and is therefore more suitable for wheelchair navigation.

OSM also proposes a smoothness classification scheme (*excellent* to *impassable*), but its use is limited due to the difficulty of consistent assessment and sensitivity to weather conditions. Only 3.43% of the road network and 2.87% of sidewalks (*highway=footway* + *footway=sidewalk*) carry smoothness tags. Notably, the key *smoothness* appears most frequently on *cycleway*, *footway*, and *track* features.

4.2.4 Inclination and Slope

Steep gradients on streets and sidewalks significantly affect wheelchair mobility and increase travel effort, making reliable gradient information essential for accessible routing. In OSM, slopes are recorded using the key *incline*, but coverage in the study area is limited: only 4.94% of roads, 3.41% of streets with sidewalk information, and 6.00% of separately mapped sidewalks contain gradient tags. Many features use the placeholder values *incline=up/down*, which provide no quantitative information and are therefore insufficient for wheelchair-relevant assessments.

To complement these gaps, a digital terrain model derived from airborne laser-scanning data is used to verify and refine gradient estimates. Elevation tiles in GeoTIFF format[23] with a ground resolution of $1 \times 1\ m^2$ (flight period 2008–2012) form the basis of this analysis (Figure 7). Outliers in the DEM-derived gradients are removed by excluding all values with a z-score greater than 3σ to ensure a representative dataset.

The downloaded raster is imported into a Postgres database and cropped to the project area using the

---

[22] https://wiki.openstreetmap.org/wiki/Key:surface

[23] https://gis.stmk.gv.at/atlas2/ogd_download.html

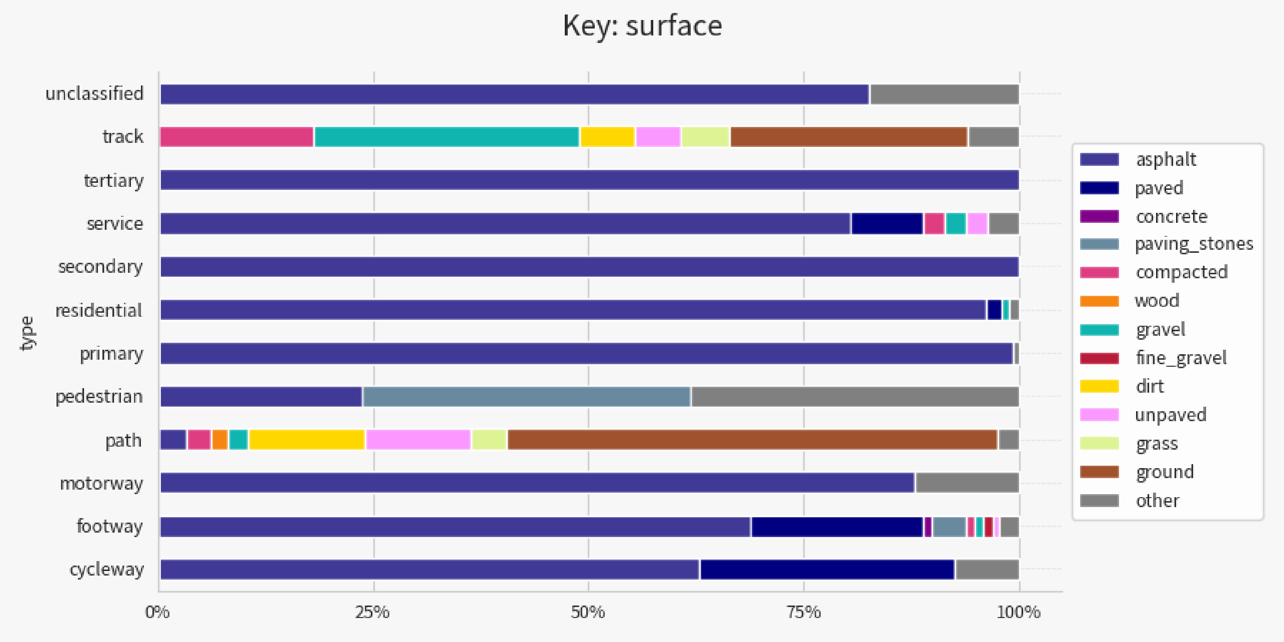


Figure 6. Surface per road type

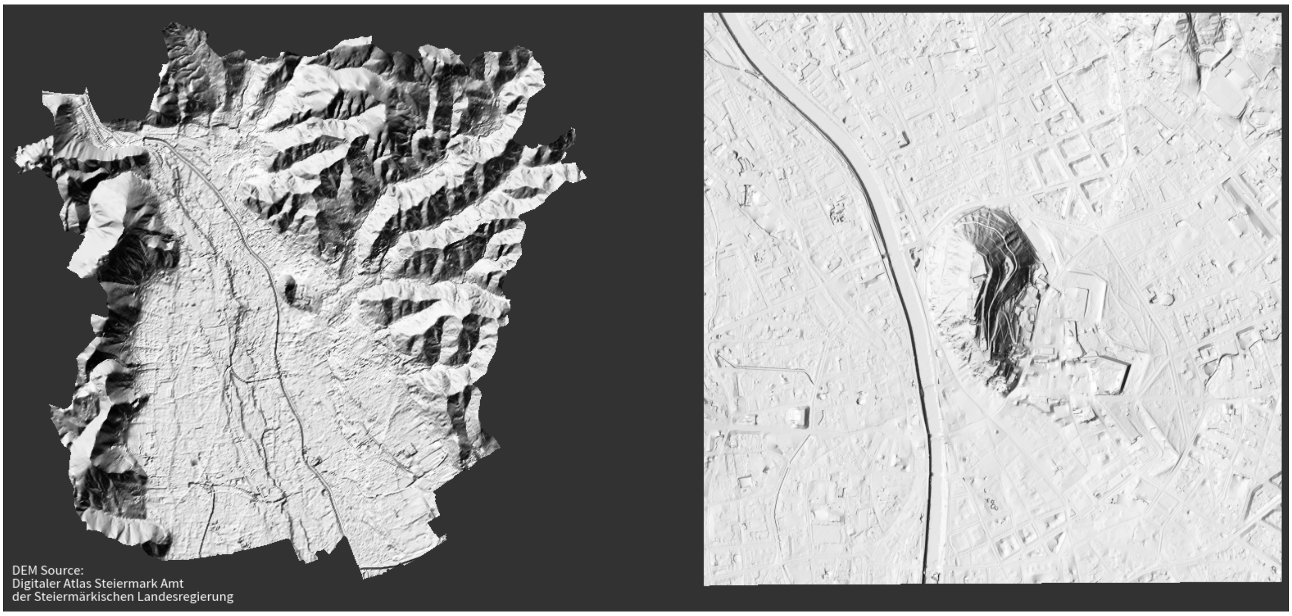


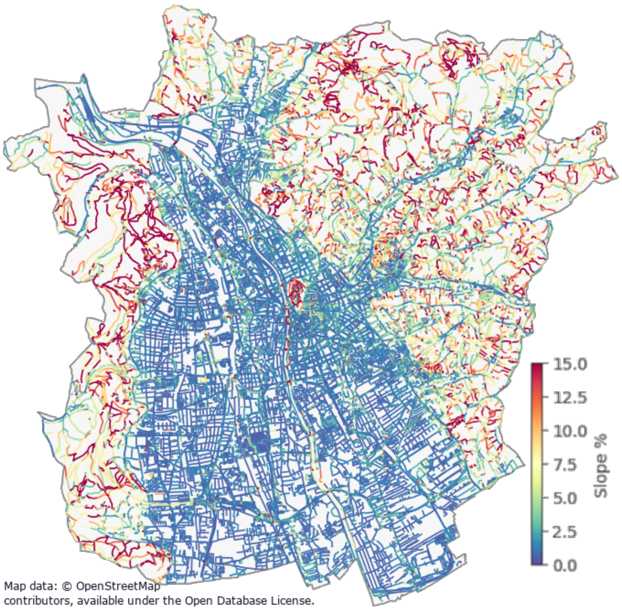
Figure 7. DEM Graz

raster2pgsql tool. To get the gradient ot the street, the Postgis command *ST_DumpAsPolygons* is used initially. This performs a polygonization of the raster data. Subsequently, the entire road network is partitioned, adopting a maximum segment length of 5 meters for enhanced precision. These discrete segments are then intersected with the vectorized elevation data. Ultimately, the segments are reassembled into their original roads, with the mean value of the segments being calculated. Figure 8 shows all streets within the specified region, with the associated gradients depicted using a color-coded scheme.

Figure 9 shows a histogram depicting the distribution of slopes in percent. The median gradient for all roads, as shown in the box plot, is approximately 1.66%. The mean value for the tested area is about 3.33%. It should be noted that these values are calculated without outliers.

Comparison between DEM and OSM data

Since both OSM and DEM provide information about elevation, it is interesting to compare them. As the DEM gradient data has several outliers, they are removed in order to be more representative. More precisely, all values



Map data: © OpenStreetMap contributors, available under the Open Database License.

Figure 8. Gradient Visualization of all Streets in Graz (in percent)

with a z-score greater than 3 sigma are removed for the following comparison (using scipy.stats.zscore > 3). The essential statistical parameters are shown in Table 3. The analysis includes all segments for which both OSM incline and DEM data are available.

Table 3. Comparison DEM and OSM Data given in both datasets

Parameter	gradient_dem	gradient_osm	unit
count	1794	1794	[#]
mean	5.99	7.33	[%]
median	3.98	4.50	[%]
std	5.56	6.44	[%]
min	0.00	0.00	[%]
max	36.87	44.00	[%]

From the total 1,794 elements present in both datasets, the median value for the DEM dataset is 5.99%, while the median value for the OSM dataset is 7.33%.

Furthermore, the range of data can be compared. It is striking that values exceeding 40% occur in the OSM data. Additionally, it is notable that in the digital elevation model, a greater number of values fall within the lower 0-2% range, whereas in OSM, more values appear between 4% and 6%. The digital elevation model exhibits, on average, lower values. Determining a more accurate value is challenging. OSM data is user-generated and thus prone to errors. The digital elevation model data is obtained through an automated process and may also contain errors. Consequently, it is difficult to ascertain which value is more accurate. However, it is conspicuous that the OSM data displays higher values, potentially indicating that users may be less skilled at estimating road gradients compared to an automated method.

4.2.5 Steps, kerbs, and other barriers

Steps:
To overcome height differences, it is inevitable for pedestrians to use steps. This simple task is not straightforward for wheelchair users. Only with the help of ramps can mechanical wheelchair users overcome such height differences. In OSM, steps are tagged using the key-value combination *highway=steps*. In the study area, there are a total of 1,154 occurrences of this combination, with a high concentration in the city center (Figure 11).

Among all steps, 38.47% have information about the presence of ramps. Whether wheelchair users can actually use the ramp is still unclear and difficult to determine. Some of these ramps are equipped with the additional key-value combinations *ramp:wheelchair=yes/no* or *wheelchair=yes/no*, although this is quite rare.

The accumulation of stairs in the city center of Graz is noticeable. The primary reason is that the Schlossberg in Graz[24], with a height of 123 m above the Graz main square, a total of 260 steps lead up the hill.

Kerbs:
A kerb (American English curb) is defined as the edge where a road meets a sidewalk[25]. In OSM, it is identified with the key *kerb*. The following values are officially documented: *flush*, *lowered*, *no*, *raised*, *rolled*, and *yes*. An essential consideration for wheelchair navigation is that the values given already indicate wheelchair accessibility. The tag *wheelchair=** can therefore be omitted. Table 4 provides information about the mentioned keys with the expected height according to (Koch-Schmuckerschlag and Kalamidas, 2006).

Value	Typical height	Implies	Graz amount
flush	∼0 cm	wheelchair=yes	1096
lowered	∼3 cm	wheelchair=yes	2110
no	—	wheelchair=yes	91
raised	>3 cm	wheelchair=no *	225
rolled	-	wheelchair=no	20
yes	any	wheelchair=no *	1

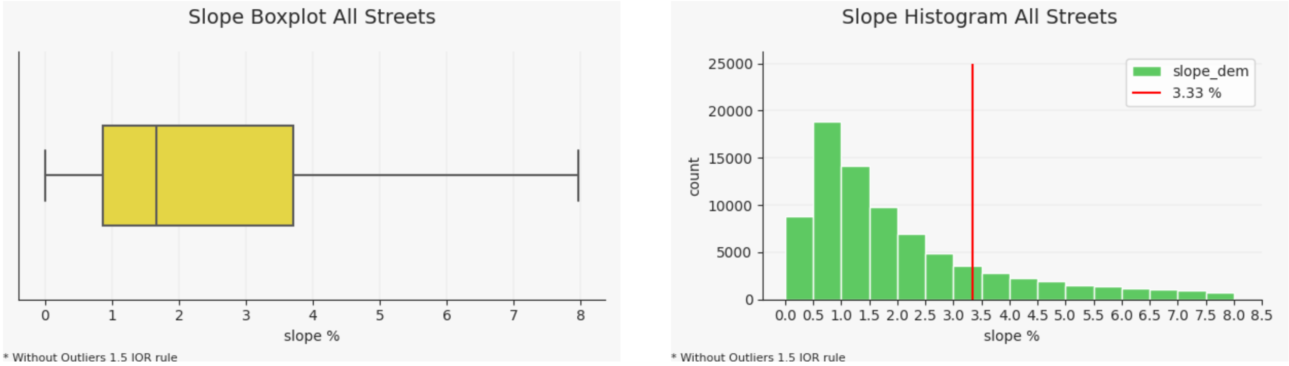
Table 4. Kerb Type

Unlike the previously analyzed tags, information about kerbs is provided with the node data type. Although the tags *barrier=kerb* and *kerb=** exist for line elements, they

---

[24] https://www.stadt-graz.at/sehenswuerdigkeiten/schlossberg-graz.html

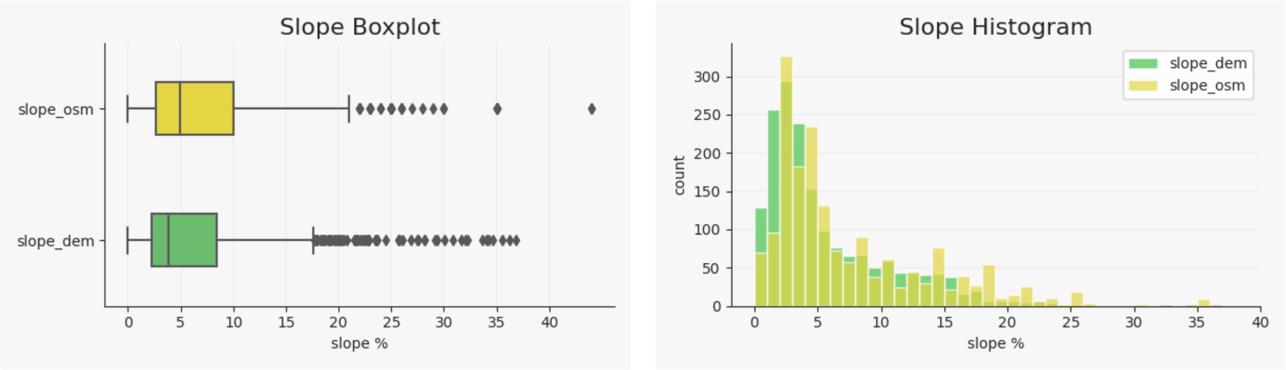
[25] https://www.oxfordlearnersdictionaries.com/definition/english/edge_1?q=edge



(a) boxplot

(b) histogram

Figure 9. Gradient Distribution of all Streets in Graz



(a) Boxplot

(b) Histogram

Figure 10. Comparison of OSM - Incline Data vs. DEM Data (in percent) for all Streets in Graz

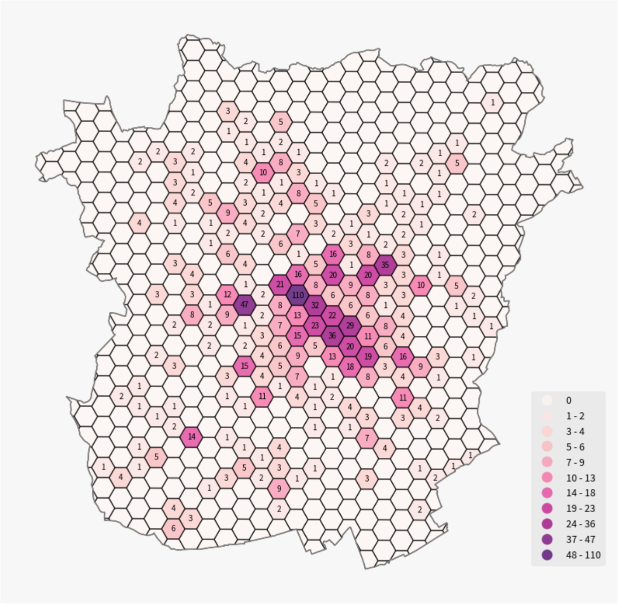


Figure 11. Hexagon map of steps (highway=steps) in Graz.

are rarely or never used. In order to include the nodes in the wheelchair routing network for later analysis, the two different data types are combined. Since the nodes are not located directly on the line elements, a Nearest Neighbour Search Analysis is performed. With the help of the Postgis command *ST_DWithin*, all kerb elements within one meter of the nearest line are included. Along with the key *kerb*, the key *kerb:height=* is frequently used. When the exact height of the kerb is known, it can be specified in centimetres. In Graz, 44.8% of all kerbs have a more accurate height specified in centimetres. The distribution of the height can be viewed in Figure 12.

Width:
The values of the key *width* for route planning for wheelchair users have to be considered as well. In total, out of all the paths, 4.22% are provided with information about width. Among the highway types, the most common ones are *footway, path, and track*. According to the regulations of the Graz city administration, a minimum dimension of 1.5 m is required to be considered wheelchair passable (Koch-Schmuckerschlag and Kalamidas, 2006).

Other Barriers:
Furthermore, there can be other obstacles and barriers in wheelchair navigation. The OSM key *barrier* is

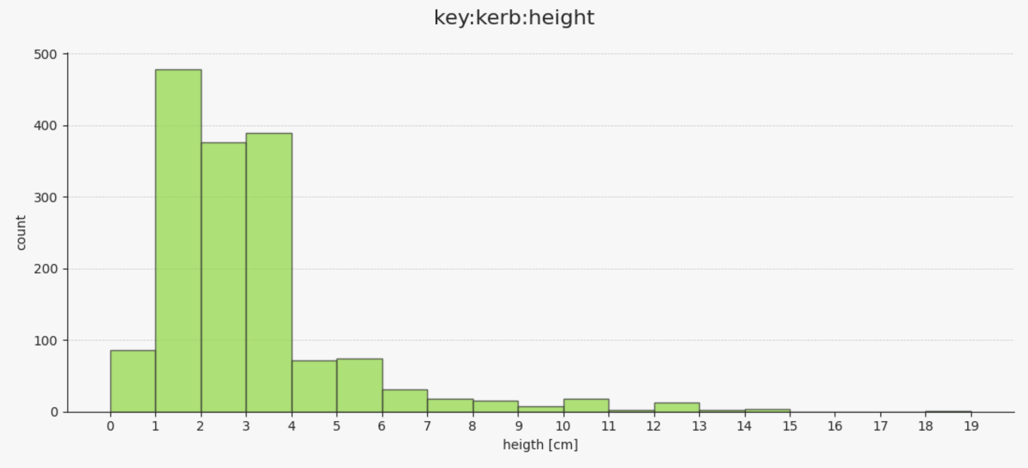


Figure 12. Heights of kerbs in the study area

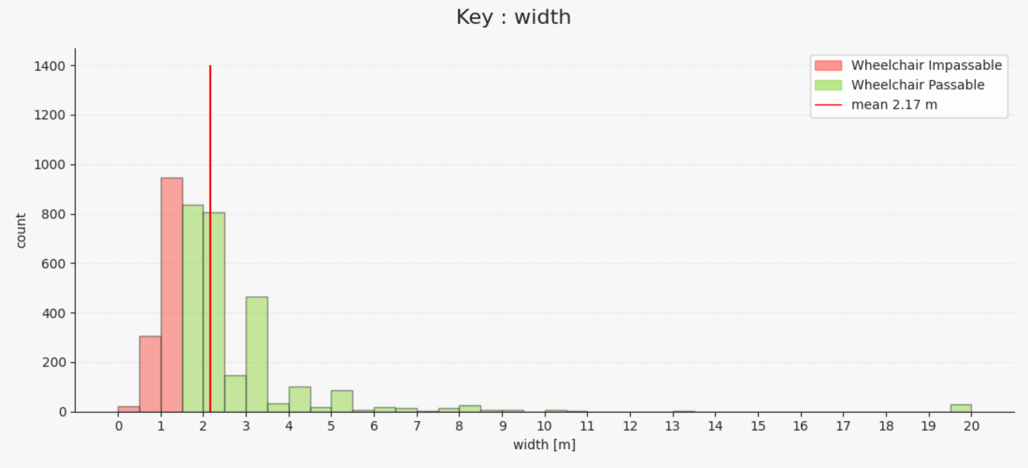


Figure 13. Width information given for the street network in the study area

particularly suitable for this purpose. Figure 14 shows the most important values; listed according to their count.

From Figure 14, it is evident that the key-value pair *barrier=gate* is by far the most prevalent within the test area, followed by *barrier=block* and *barrier=liftgate*. According to the OpenStreetMap Wiki, a "gate" refers to an entrance that can be opened or closed to traverse the barrier. It is frequently combined with the key *empf=**. This is particularly significant for wheelchair navigation, as such gates typically present impassable obstacles. Furthermore, bollards and cycle barriers influence route planning. In many instances, these barriers are impassable for wheelchair users.

4.3 Wheelchair Network Parameters

After a detailed analysis of individual tags, Table 5 summarizes all the considered elements. Based on them, a network is built for further testing of the routing capability. From the initial overall network with a total length of 2,947 km (92,231 elements), the created wheelchair-routable network is reduced to 1,503 km (56,820 elements).

The parameters used in the analysis consider both line and node data. The following parameters are particularly important for the establishment of the wheelchair-routing network and are therefore analyzed in detail: street type, surface, sidewalk information, obstacles, and nodes with kerb information.

It is important to note that bridges over the river "Mur" in the test area of Graz were added manually to the parameters. This is because bridges over rivers were removed based on the DEM analysis and the slope criteria. Consequently, there were large differences in terrain that would be insurmountable for wheelchair users. An exception via the OSM key *bridge* is not possible, as the terrain model exhibits irregularities prior to the beginning of the bridge.

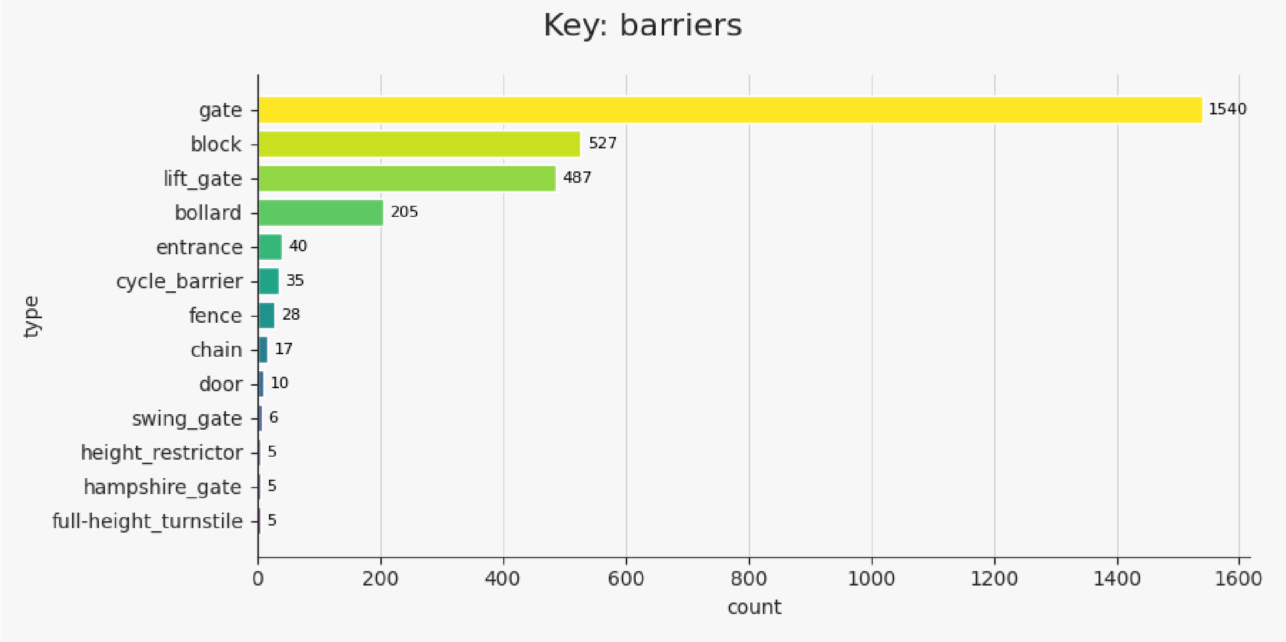


Figure 14. Barriers in Graz: Bar Chart Depicting the Most Common Barrier Types in the Study Area

Table 5. Wheelchair Network Parameters

Parameter	Key	Wheelchair Parameters (Values)
Street Type	highway	footway, service, residential, path, cycleway, pedestrian, tertiary, unclassified, living_street, secondary_link, tertiary_link
	footway	sidewalk, crossing, traffic_island, link, island, yes, path, ramp
Surface	surface	asphalt, paved, paving_stones, ground, concrete, sett, cobblestone, cobblestone:flattened, metal, asphalt;paving_stones, asphalt;cobblestone, concrete:plates, asphalt;concrete, rock, stone, concrete:lanes, carpet, marble, metal_grid, mud, grav, unhewn_cobblestone, pebblestone:lanes, stainzerplatten
	smoothness	excellent, good, intermediate
Service	service	driveway, parking_aisle, alley, drive-through, spur, slipway, yard
Sidewalk	sidewalk	both, separate, right, left, none, explicit, yes, seperate;marked
	sidewalk:right	separate, yes
	sidewalk:left	separate, yes
	sidewalk:both	separate, yes
	sidewalk:width	$>$ 1.5 [m]
	sidewalk:surface	
	sidewalk:smoothness	*same as parameters from *Surface*
	sidewalk:incline	$<$ 10 %
Obstacles	ramp	yes, separate
Others	access	yes, permissive, destination, designated, service, discouraged
	foot	yes, designated, permissive, official, residents
	width	$<$ 1.5
	incline	$<$ 6%
	wheelchair	yes, limited, designated
	crossing	
	barrier	fence, wall, railing, log, kerb, handrail
Nodes	barrier	kerb, gate, block, lift_gate, bollard, entrance, cycle_barrier, fence, chain, door, swing_gate, full-height_turnstile, yes, hampshire_gate, stile, turnstile, toll_booth, kissing_gate, sally_port, wall, trunk, blocks, jersey_barrier, log
	kerb	flush, lowered, no
	kerb:height	$<$ 3 cm

5 Experiments

To gain insight into the chosen parameters, we perform several routing tasks using the network established earlier with the parameters listed in Table 5 as the Wheelchair Network. As a reference, we also include an additional pedestrian route that utilizes the same types of roads (highway, footway, and sidewalk) but does not consider wheelchair-specific parameters such as surface or gradient.

5.1 Experiment 1

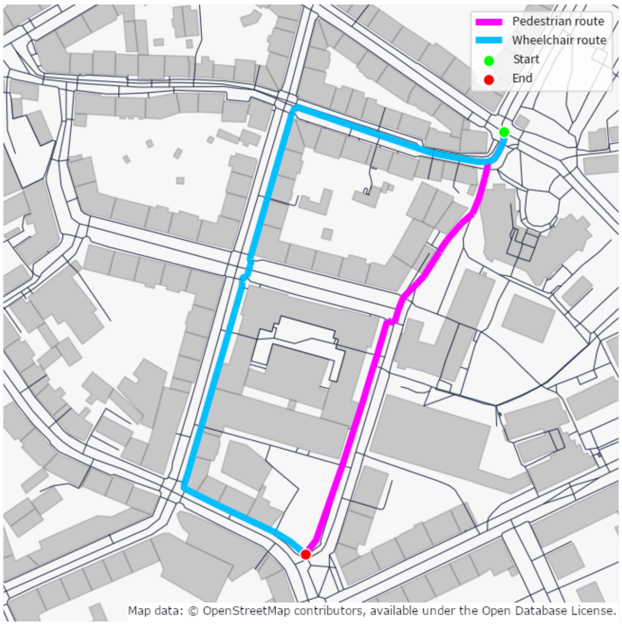
As a first experiment, a routing problem in the surroundings of the 'TU Graz - Neue Technik' is chosen. The Dijkstra's algorithm is used as the routing algorithm. The distance is defined as the cost.

As shown in Figure 16, the two routes vary significantly. The routes separate only a few meters after the start. Table 6 summarizes the differences. The route for wheelchair users is about 200 meters longer than the pedestrian route. It also indicates that the pedestrian route is steeper. The maximum gradient is about 10%. Figure 15 shows a photograph of this key location.

Table 6. Comparison Wheelchair vs. Pedestrian

	Wheelchair	Pedestrian	[unit]
Length	508	314	[m]
Segments	33	23	[#]
Slope_DEM Mean	1.84	3.49	[%]
Slope_DEM Max	5.88	10.60	[%]
Width Min	1.9	None	[m]

Figure 15. Photograph of the critical location (source: Mapillary)



Map data: © OpenStreetMap contributors, available under the Open Database License.

Figure 16. The pedestrian and wheelchair routes in Experiment 1.

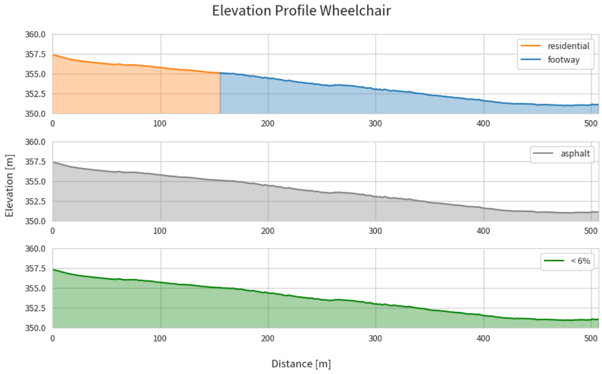


Figure 17. Experiment 1; Elevation Profile Wheelchair

Furthermore, the two different paths are analyzed in detail. Hence, we represent the routes with the help of elevation profiles. Figures 17 and 18 show the elevation profiles. From these figures, it is obvious that the distance of the wheelchair route is longer than the pedestrian route. In contrast, it is easy to see that the pedestrian route is considerably steeper. Particularly noticeable is the pedestrian route's gradient increase between 50 and 120 meters (see Table 5).

Regarding the type of road, the pedestrian route uses the road type: *residential*, *service*, *cycleway* and *footway*. On the contrary, the wheelchair path uses only the two types *residential* and *highway*. The surface condition is not decisive. Both of them are predominantly surfaced with *asphalt*. Only a short section of the pedestrian route has an unknown surface type (i.e., surface=None). Therefore, the surface in this segment is not defined properly in the OSM.

5.2 Experiment 2

For the second experiment, we selected a route neighboring the Graz City Park. We calculated both a wheelchair route and a pedestrian route for this location.

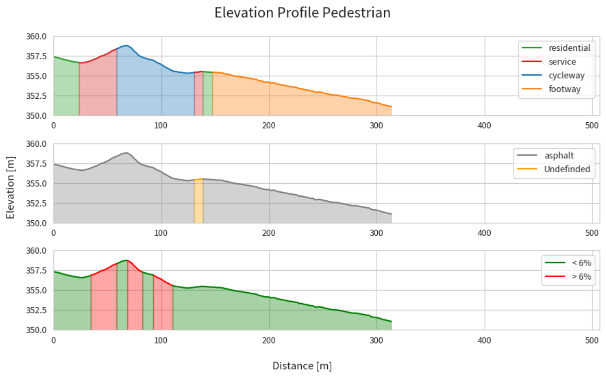


Figure 18. Experiment 1; Elevation Profile Pedestrian

Table 7. Comparison Between Wheelchair and Pedestrian Routes in Experiment 2

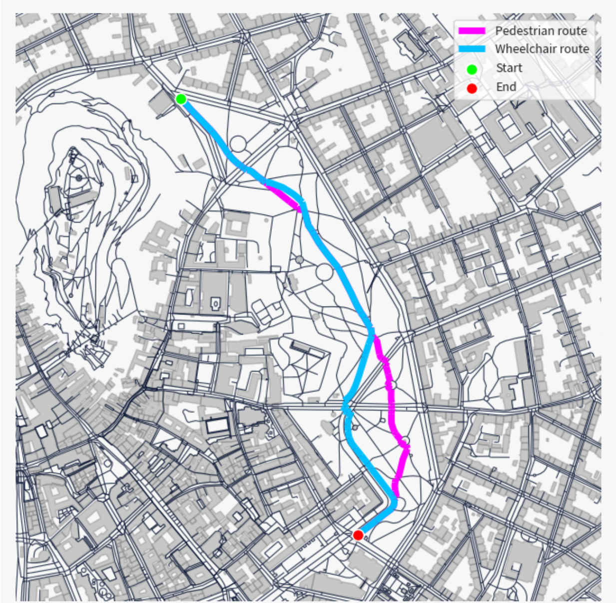
	Wheelchair	Pedestrian
length	1721.27 [m]	1230.5 [m]
segments	91	84
Slope_DEM Mean	2.34%	3.11 %
Slope_DEM Max	8.5%	22%
Slope_OSM Max	5%	20%
Width Min	1.8 [m]	None

As in the first experiment, the pedestrian route is significantly shorter. What makes this example interesting is that the two routes diverge in the first half, become identical in the middle section, and then diverge again until the endpoint.

Table 7 presents the important parameters. It shows that the wheelchair path is approximately 491 m longer than the pedestrian path. The maximum gradient is a key factor in this experiment. Here it is 8.5% according to the digital elevation model and 5% according to the tagged OSM data. In contrast, the pedestrian route has a significantly higher gradient of 22% (DEM) or 20% (OSM). This suggests that the difference in path length may be due to the difference in maximum gradient. Consequently, wheelchair users may need to choose an alternative route due to the gradient of pedestrian paths.

The differing fastest routes between the wheelchair and pedestrian networks, gave us a hint for a closer examination of both paths using elevation profiles.

In terms of road type, the two scenarios do not differ significantly. Both use only footways and cycleways. The critical factor is the surface condition. After about 780 meters of the pedestrian route, the fastest route leads through a park. Accordingly, the road surface changes as well. Especially the two surface tags *surface=pebblestone* and *surface=fine_gravel* are not passable for wheelchair users. Analyzing the gradient, a red section (> 6%, Figure 20) in the last part of the pedestrian route stands out. In this section, the gradient is over 20%.



Map data: © OpenStreetMap contributors, available under the Open Database License.

Figure 19. The pedestrian and wheelchair routes beween the origin (green) and destination (red) points in Experiment 2.

5.3 Experiment 3

A performance test evaluates the usability of the routing algorithm by comparing the full, pedestrian, and wheelchair networks (see Figure 22). Start and end points are randomly chosen from nodes common to all networks, located within 1 km of Graz's city center. Dijkstra's algorithm computes the shortest paths based on segment length, producing 1000 origin–destination pairs. Another condition is that the starting point is of the type highway = 'footway', 'service', 'residential', 'path', 'cycleway', 'pedestrian', 'tertiary', or 'living_street'.

The wheelchair network shows the most failed route calculations because of its strict constraints, resulting in many non-routable segments and isolated road sections. As Table 8 indicates, wheelchair routes are also the longest, since elevation limits often force substantial detours.

The distributions of road types and surface conditions are similar across networks (see Tables 10 and 11), but the wheelchair network differs notably: footway dominates instead of pedestrian, largely because highway=pedestrian often has steeper gradients and less suitable surfaces. For wheelchair users, asphalt is most common, while rough surfaces like cobblestone, gravel, or sett appear far less frequently.

In addition, the distribution of the surface texture is given graphically in Figure 23. Again, the deviation of the wheelchair route calculations from the other two can be seen.

Finally, information about kerbs is listed in Table 12. The number of route segments with kerbs is relatively large for pedestrians and overall compared to the wheelchair

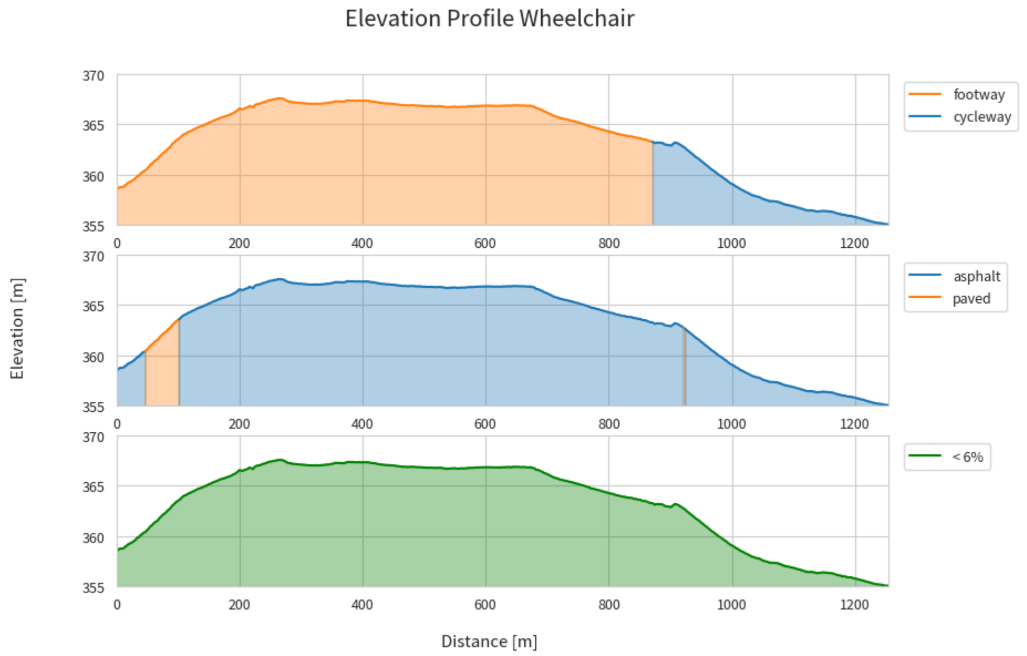


Figure 20. Experiment 2; Elevation Profile Wheelchair

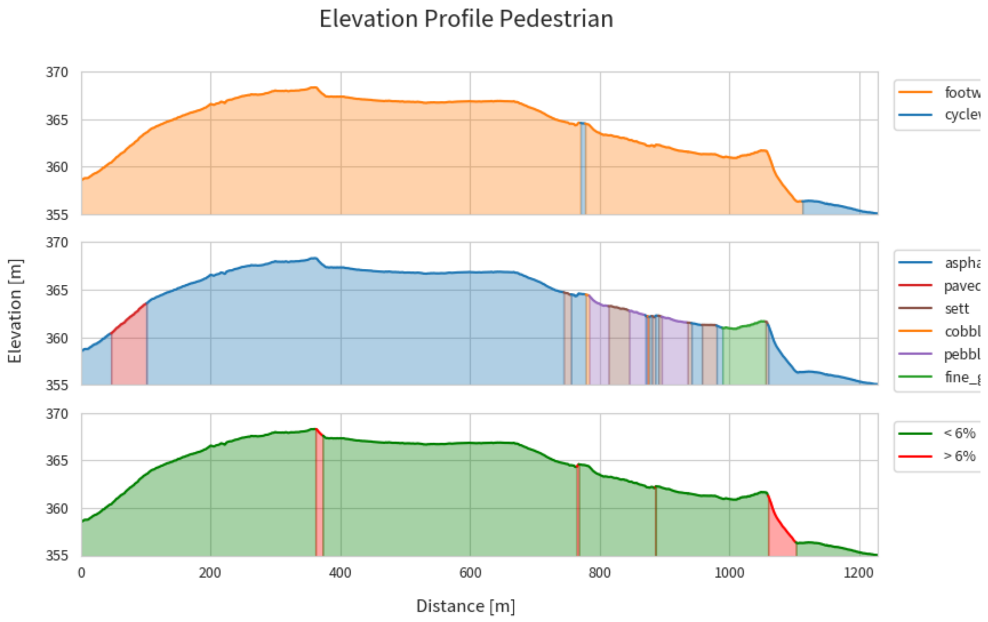


Figure 21. Experiment 2; Elevation Profile Pedestrian

Table 8. Route Statistics

	All Streets	Pedestrian Network	Wheelchair Network	[unit]
Testsize	1000	1000	1000	[#]
No Route Possible	3	3	314	[#]
Sum Length	759.00	762.90	647.26	[km]
Average Length per Route	759.00	762.90	647.26	[m]
Average Slope	3.13	3.20	2.04	[%]
Count of Streets Slope $> 6\%$	32[1]	6712	6040	[#]

[1] differs from zero because bridges are included in the calculation (see Section 4.3)

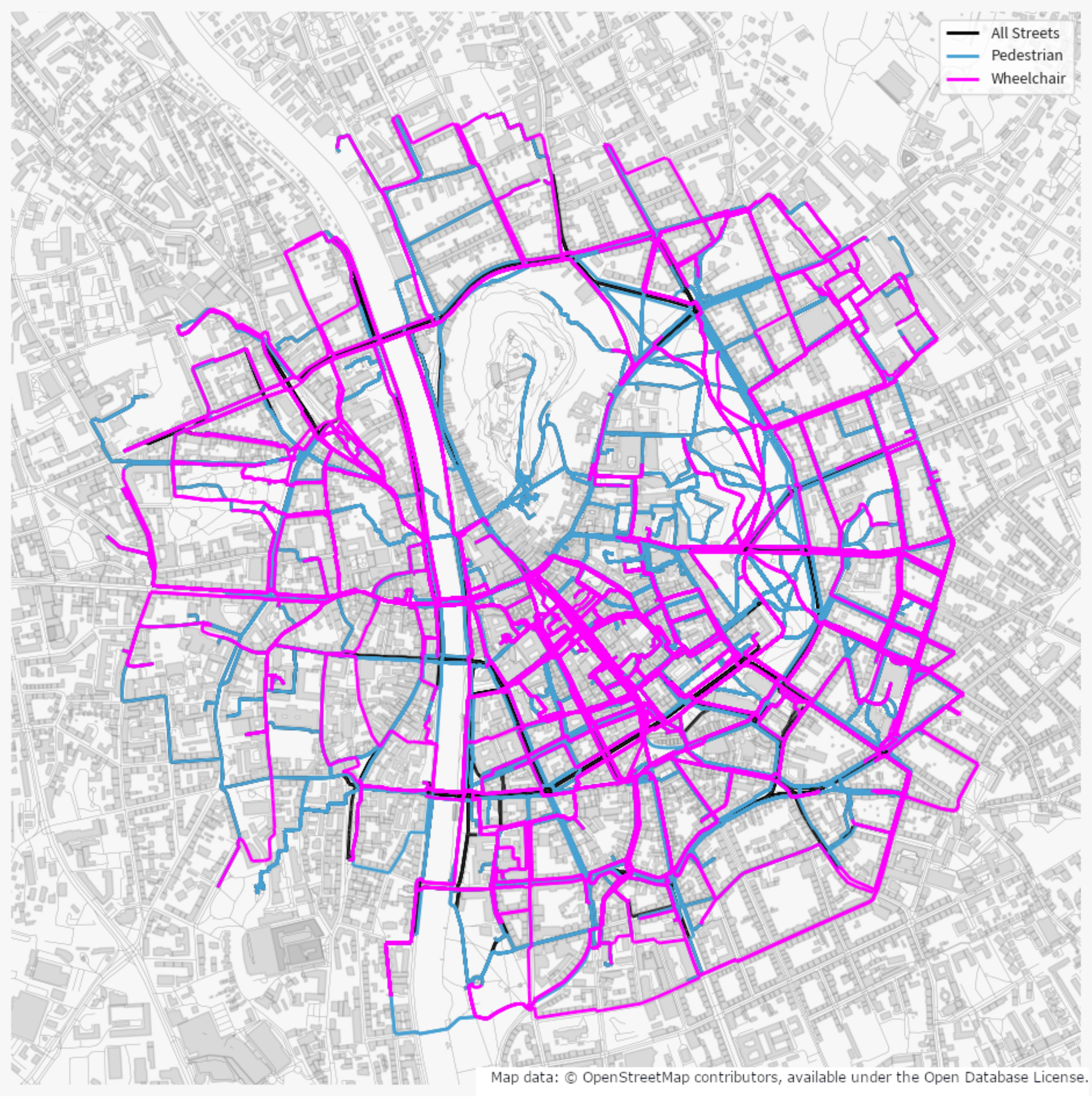


Figure 22. Overview Map Experiment 3 in Graz with 1000 Random Routes for the Three Networks (All Streets, Pedestrian Network, Wheelchair Network)

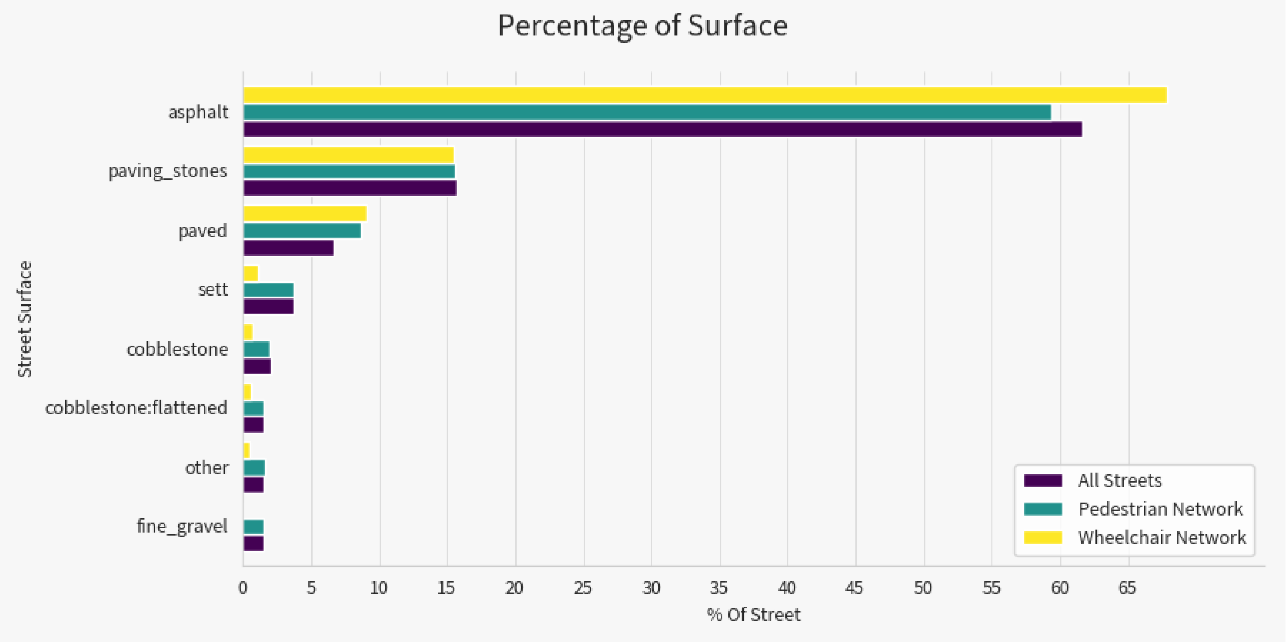


Figure 23. Detailed Surface Conditions for the Three Networks

Table 9. OSM Tag Analysis for Various Network Types in Experiment 3

Table 10. Analysis of Surface Types for Three Distinct Network Categories

surface=	All	Pedestrian	Wheelchair
asphalt	61.7%	59.3%	67.9%
paving_stones	15.7%	15.7%	15.5%
paved	6.7%	8.6%	9.1%
sett	3.7%	3.8%	1.1%
cobblestone	2.1%	2.0%	0.7%
fine_gravel	1.5%	1.5%	0.0%
cobblestone-flattened	1.5%	1.6%	0.6%
other	1.5%	1.7%	0.5%

Table 11. Analysis Regarding Highway Type for 3 Different Network Types

	All	Pedestrian	Wheelchair
highway=			
footway	35.3%	45.9%	39.1%
residential	21.4%	16.8%	20.5%
pedestrian	19.1%	18.7%	18.5%
primary	7.5%	2.6%	0.0%
secondary	5.4%	1.7%	0.0%
cycleway	4.7%	9.0%	18.9%
service	3.5%	3.2%	1.8%
other	1.4%	1.4%	0.5%
unclassified	1.1%	0.0%	0.1%

Table 12. Detailed Kerb Type Analysis for the Three Networks

kerb	All Streets	Pedestrian Network	Wheelchair Network
flush	4417	6556	7034
lowered	4050	5624	5145
no	409	548	517
raised	837	1186	0
rolled	104	134	0
yes	71	29	0

network. This differentiates the wheelchair network from the pedestrian network.

6 Comparison of different cities

Cities of similar size to Graz are chosen for a comparison and applicability to other geographical contexts. The two Austrian provincial capitals, Linz and Salzburg, are well suited for this task. A buffer with a radius of 2 kilometers is created around the city center. All subsequent analyses will be based on these subsets. To simplify the model, there is no analysis of the gradient in the comparison. The results for the different cities are presented in Figure 24. The complete road network of each city, without any limitations, is displayed.

The most important statistical parameters are given in Table 13. In terms of the number of line segments, the cities of Graz and Linz differ only slightly. The street network length is also similar in both cities. Salzburg has a significantly smaller street network length and also

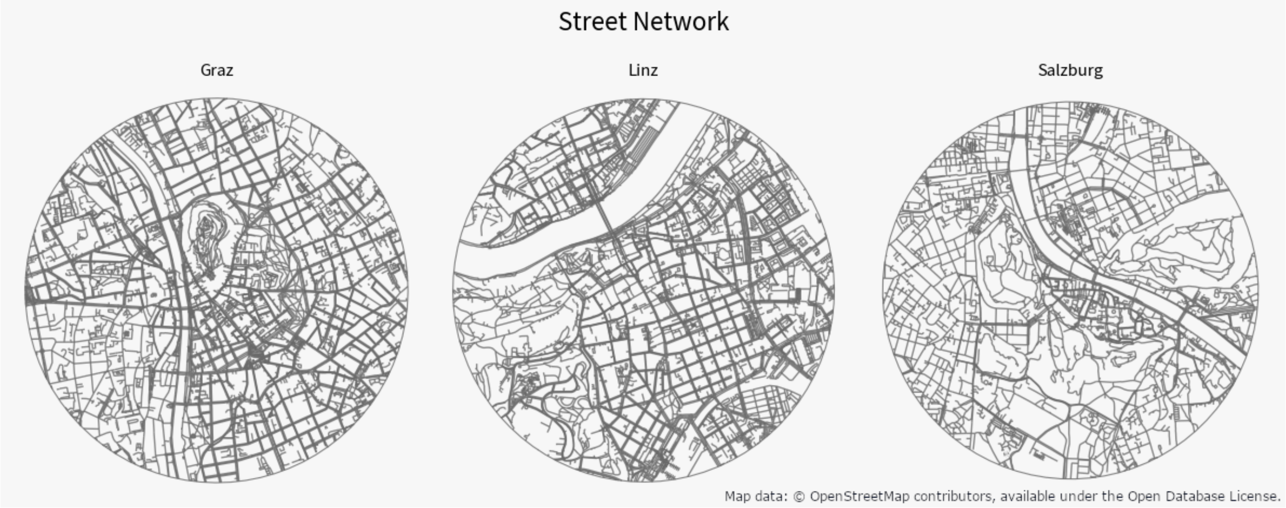


Figure 24. City Comparison - All streets

a smaller total number of street segments. This fact is underpinned by a lower street density.

The differences among the sidewalks are also recorded in the table. Three categories have been taken into consideration. Analogous to Chapter 4.2.2, these result in *sidewalk*=, *highway=footway*, *footway=sidewalk*, and sidewalk_unique. The outcomes are visible in Figures 25 through 27. From these figures, as well as from Table 13, it emerges that Linz is particularly weakly mapped with *sidewalk*=. On the other hand, Salzburg has only about 6km of pavements marked as its own way with *highway=footway*, *footway=sidewalk*. The ground truth for the total length of sidewalks in the three cities cannot be determined with Open Data. Although a dataset for Salzburg can be found on the Open Data Portal of Austria[26], it is outdated and incomplete.

---

[26] https://www.data.gv.at/katalog/dataset/ce9607e6-5d59-4980-9cd3-923661d41af0

Table 13. Comparison of three cities in Austria in terms of their street networks.

	Graz	Linz	Salzburg	$[unit]$
Area (With 2km Radius)	7.06	7.06	7.06	$[km^2]$
Count of Linesegments	24094	15649	9171	[#]
Length of whole network	387.46	357.77	234.50	$[km]$
Length Sidewalk	65.18	14.91	42.29	$[km]$
Length Sidewalk hw-fw + fw-sw[1]	119.55	87.96	6.84	$[km]$
Length Sidewalk unique	129.39	91.05	41.74	$[km]$
street_density_km	54870.42	50666.76	33208.82	$[\#/km^2]$
streets containing key: wheelchair=*	388	1251	178	[#]
Kerb Count	2233	52	96	
Kerb per km of Streets	5.76	0.15	0.41	$[\#/km]$
Kerb per km^2	316.23	7.36	13.6	$[\#/km^2]$
Steps per km^2	436	327	209	$[\#/km^2]$

[1] *highway = footway, footway = sidewalk*

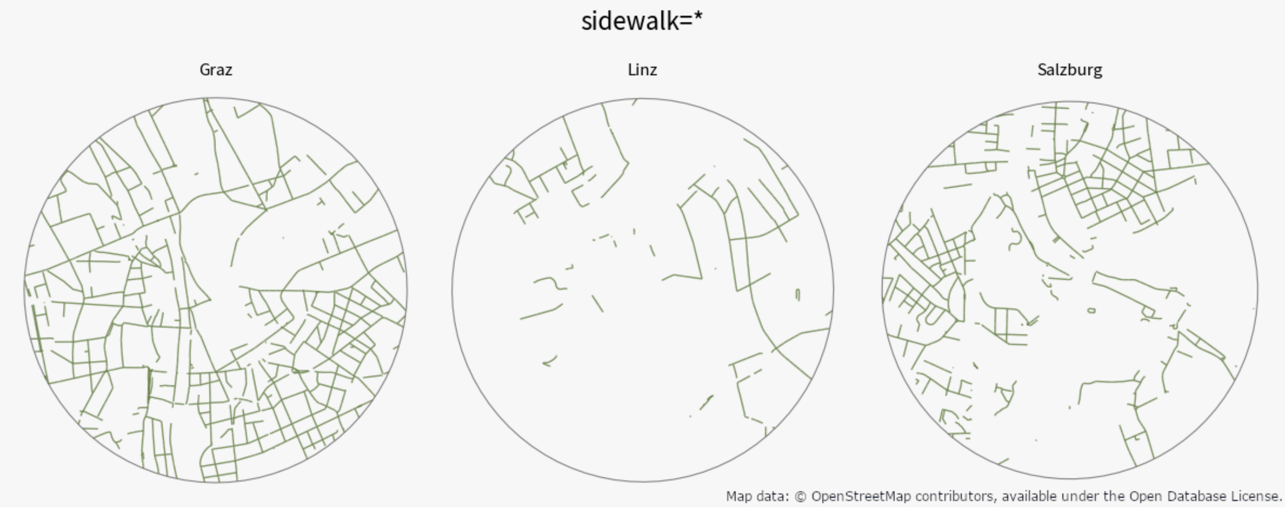


Figure 25. City Comparison - Sidewalk=*

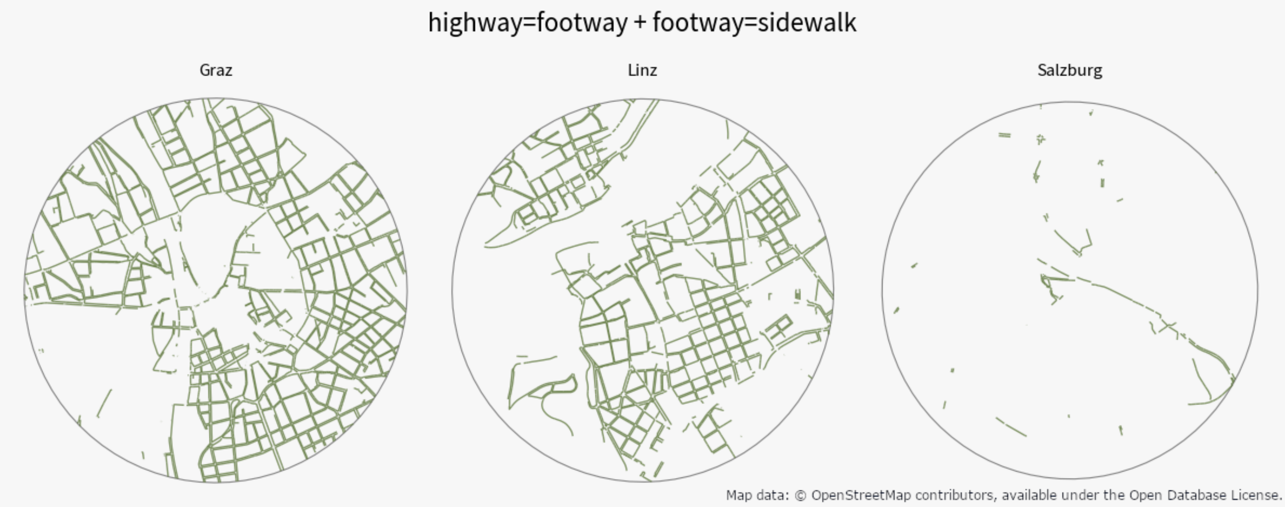


Figure 26. City Comparison - Highway = Footway and Footway = Highway

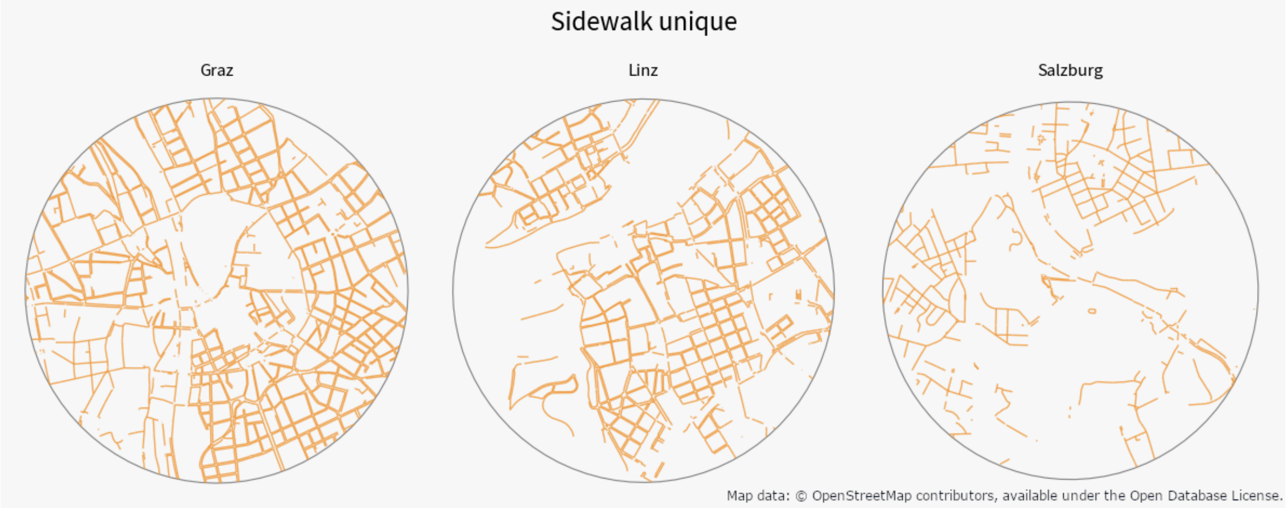


Figure 27. City Comparison - Sidewalk unique

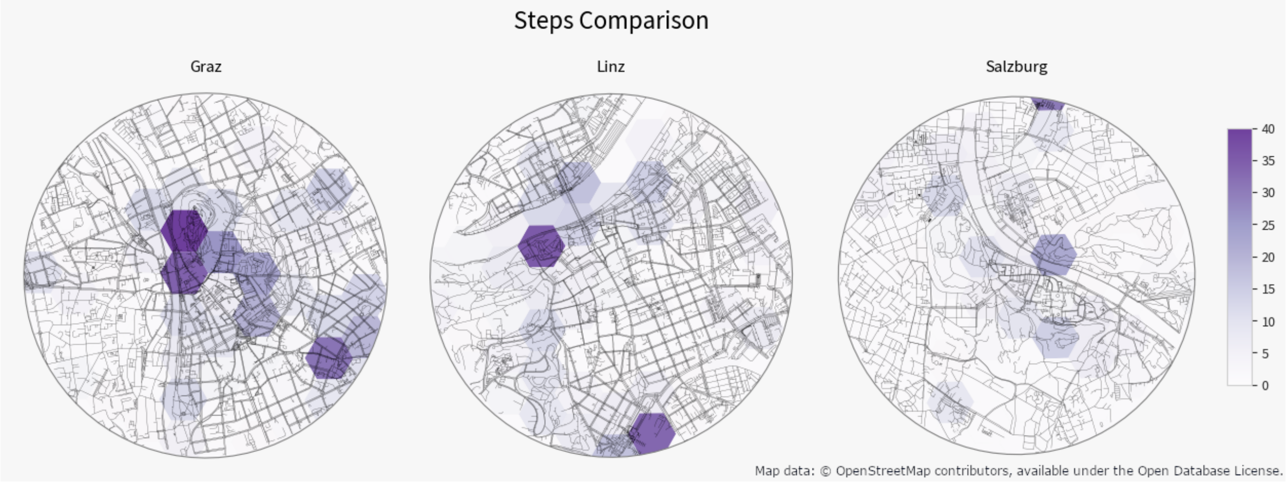


Figure 28. City Comparison - Hexagon Map Sidewalk

7 Conclusion and Future work

Routing is common in everyday life, and routing apps are especially useful in complex urban environments. This paper examines how various OSM-based parameters—such as surface, gradient, width, smoothness, barriers, steps, and ramps—affect wheelchair navigation. A major challenge is inconsistent sidewalk tagging, with separate-path tagging proving more suitable, though sidewalk completeness cannot be reliably assessed due to missing reference data. Furthermore, gradient is a critical factor (Gharebaghi et al., 2021; Tannert and Schöning, 2018; Beale et al., 2006), and OSM's incline tag is insufficient. Reliable wheelchair routing requires external elevation data such as the Open Elevation Service. Barriers like steps and kerbs must be precisely located, yet kerb data stored mainly in nodes requires spatial joins, and data density varies widely between cities.

In this study, a simplified routing network is built using parameter-based whitelisting and compared to a pedestrian network. Experiments in Graz show that, compared to pedestrian routes, wheelchair routs often require significant detours increasing the trip distance and duration. They also shaw that gradients—especially above 6%—often prevent feasible wheelchair routes, leading to many disconnected origin-destination pairs. To address this, future work will explore transitioning from strict constraints to multi-criteria routing costs by assigning variable weights to accessibility factors such as slope, surface conditions, and kerb heights within the routing cost function. This will enable the algorithm to better reflect the real-world effort required by wheelchair users. It would also allow for a more nuanced personalization of routing based on the user's actual characteristics such as the type of wheelchair (e.g., manual or electric), physical capabilities, available assistance, and so on.

Furthermore, our methodology demonstrates the theoretical capabilities of an OSM- and DEM-based wheelchair routing network, with current findings reflecting only the computational analysis based on the available data. Future research should include field experiments with wheelchair users in the same localities to compare against and validate the computational results.

Finally, our initial multi-city comparison between Graz, Linz, and Salzburg highlights major differences in OSM data quality, particularly concerning sidewalk standardization and completeness. Future research will expand on this by extending the methodology to other cities and countries. Broadening the geographical scope will help assess the global feasability of OSM for wheelchair routing, further highlighting the need for standardized sidewalk mapping practices and the completeness of sidewalk data, as well as the development of routing algorithms that comprehensively consider and prioritize sidewalks and other pedestrian infrastructure.

Declaration of Generative AI in writing

The authors declare that they have not used Generative AI tools in the preparation of this manuscript. AI tools were not used 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.

Code and data availability

The software repository containing pre-processed data and code used to obtain the results of this study is available online with DOI https://doi.org/10.6084/m9.figshare.31333180.

References

Andreev, S., Dibbelt, J., Nöllenburg, M., Pajor, T., and Wagner, D.: Towards realistic pedestrian route planning, OpenAccess Series in Informatics, 48, 1–15, https://doi.org/10.4230/OASIcs.ATMOS.2015.1, 2015.

Barczyszyn, G. L., Camenar, L. M. D., Nascimento, D. F. D. D., Kozievitch, N. P., Silva, R. D. D., Almeida, L. D., Santi, J. D., and Minetto, R.: A collaborative system for suitable wheelchair route planning, ACM Transactions on Accessible Computing, 11, https://doi.org/10.1145/3237186, 2018.

Beale, L., Field, K., Briggs, D., Picton, P., and Matthews, H.: Mapping for Wheelchair Users: Route Navigation in Urban Spaces, The Cartographic Journal, 43, 68–81, https://doi.org/10.1179/000870406X93517, 2006.

Bolten, N., Amini, A., Hao, Y., Ravichandran, V., Stephens, A., and Caspi, A.: Urban Sidewalks: Visualization and Routing for Individuals with Limited Mobility, in: Proceedings of the 1st International ACM SIGSPATIAL Workshop on Smart Cities and Urban Analytics, UrbanGIS'15, pp. 122–125, Association for Computing Machinery, https://doi.org/10.1145/2835022.2835042, 2015.

Bundeskanzleramt der Republik Österreich: RIS - Bundes-Behindertengleichstellungsgesetz - Bundesrecht konsolidiert, Fassung vom 16.09.2022, https://www.ris.bka.gv.at/GeltendeFassung.wxe?Abfrage=Bundesnormen&Gesetzesnummer=20004228, [Accessed 16-Sep-2022], 2026.

Ding, D., Parmanto, B., Karimi, H. A., Roongpiboonsopit, D., Pramana, G., Conahan, T., and Kasemsuppakorn, P.: Design Considerations for a Personalized Wheelchair Navigation System, in: 2007 29th Annual International Conference of the IEEE Engineering in Medicine and Biology Society, pp. 4790–4793, IEEE, https://doi.org/10.1109/IEMBS.2007.4353411, 2007.

Dzafic, D., Candiotti, J. L., and Cooper, R. A.: Improving wheelchair route planning through instrumentation and navigation systems, in: 42nd Annual International Conference of the IEEE Engineering in Medicine & Biology Society (EMBC), pp. 5737–5740, IEEE, https://doi.org/10.1109/EMBC44109.2020.9176481, 2020.

Edinger, J., Hofmann, A., Wachner, A., Becker, C., Raychoudhury, V., and Krupitzer, C.: WheelShare: Crowd-Sensed Surface Classification for Accessible Routing, in: 2019 IEEE International Conference on Pervasive Computing and Communications Workshops, PerCom Workshops 2019, pp. 584–589, Institute of Electrical and Electronics Engineers Inc., https://doi.org/10.1109/PERCOMW.2019.8730849, 2019.

Ferreira Olivatto, T., Stanganini, F., and Melanda, E.: Drone Imagery for OpenStreetMap Sidewalk Data Enrichment, in: LBS 2019: Adjunct Proceedings of the 15th International Conference on Location-Based Services., https://doi.org/10.34726/lbs2019.56, 2019.

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

Gjeruldsen, E.: Detecting sidewalks in OpenStreetMap using machine learning, https://hiof.brage.unit.no/hiof-xmlui/bitstream/handle/11250/2676606/Gjeruldsen_Eirik.pdf?sequence=1&isAllowed=y, (Accessed on 04/02/2023), 2020.

Goodchild, M. F.: Citizens as sensors: The world of volunteered geography, GeoJournal, 69, 211–221, https://doi.org/10.1007/s10708-007-9111-y, 2007.

Graser, A., Straub, M., and Dragaschnig, M.: Is OSM Good Enough for Vehicle Routing? A Study Comparing Street Networks in Vienna, in: Progress in Location-Based Services 2014, edited by Gartner, G. and Huang, H., pp. 3–17, Springer International Publishing, https://doi.org/10.1007/978-3-319-11879-6_1, 2015.

Haklay, M.: How Good is Volunteered Geographical Information? A Comparative Study of OpenStreetMap and Ordnance Survey Datasets, Environment and Planning B: Planning and Design, 37, 682–703, https://doi.org/10.1068/b35097, 2010.

Hossain, A. M., Mahmud, N., Han, E., Advani, N., Baral, B., Gani, M. O., and Raychoudhury, V.: A Smart and Barrier-Aware Navigation System for Wheelchair Routing, in: 2025 IEEE 22nd International Conference on Mobile Ad-Hoc and Smart Systems (MASS), pp. 717–722, IEEE, Chicago, IL, USA, https://doi.org/10.1109/MASS66014.2025.00117, 2025.

International Organization for Standardization: ISO/TC 173/SC 1 - Wheelchairs, https://www.iso.org/committee/53792.html, [Accessed 16-Apr-2026].

Kirschbaum, J. B., Axelson, P. W., Longmuir, P. E., Mispagel, K. M., Stein, J. A., and Yamada, D. A.: Designing Sidewalks and Trails for Access: Part II Of II: Best Practices Design Guide, September, U.S. Department of Transportation, Federal Highway Administration, https://www.fhwa.dot.gov/environment/bicycle_pedestrian/publications/sidewalk2/pdf.cfm, 2001.

Koch-Schmuckerschlag, D. C. and Kalamidas, D. O.: Barrierefreies bauen für alle Menschen: Planungsgrundlagen, Stadtbaudirektion Graz, Referat Barrierefreies Bauen, https://www.technik.steiermark.at/cms/dokumente/11507965_58814178/d38dda84/Broschuere_BB_01__.pdf, 2006.

Lugtigheid, F., Park, A. J., Hwang, E., Spicer, V., and Brantingham, P. L.: Sidewalk-Based Accessible Pedestrian Routing, in: 2024 IEEE 15th Annual Ubiquitous Computing, Electronics & Mobile Communication Conference (UEMCON), pp. 599–604, IEEE, Yorktown Heights, NY, USA, https://doi.org/10.1109/UEMCON62879.2024.10754683, 2024.

Matthews, H., Beale, L., Picton, P., and Briggs, D.: Modelling Access with GIS in Urban Systems (MAGUS): Capturing the Experiences of Wheelchair Users, Area, 35, 34–45, https://doi.org/10.1111/1475-4762.00108, 2003.

Mobasheri, A., Deister, J., and Dieterich, H.: Wheelmap: the wheelchair accessibility crowdsourcing platform, Open Geospatial Data, Software and Standards, 2, 27, https://doi.org/10.1186/s40965-017-0040-5, 2017.

National Academies of Sciences, Engineering, and Medicine: The Promise of Assistive Technology to Enhance Activity and Work Participation, National Academies Press (US), Washington (DC), https://doi.org/10.17226/24740, 2017.

Neis, P. and Zielstra, D.: Generation of a tailored routing network for disabled people based on collaboratively collected geodata, Applied Geography, 47, 70–77, https://doi.org/10.1016/j.apgeog.2013.12.004, 2014.

Neis, P., Zielstra, D., and Zipf, A.: The Street Network Evolution of Crowdsourced Maps: OpenStreetMap in Germany 2007–2011, Future Internet, 4, 1–21, https://doi.org/10.3390/fi4010001, 2011.

Novack, T., Wang, Z., and Zipf, A.: A system for generating customized pleasant pedestrian routes based on openstreetmap data, Sensors (Switzerland), 18, https://doi.org/10.3390/s18113794, 2018.

OpenStreetMap Wiki: Key:sidewalk, https://wiki.openstreetmap.org/wiki/Key:sidewalk, (Accessed on 02/04/2023).

Standards, A.: B 1600 ÖNORM. Barrierefreies Bauen Planungsgrundlagen-1, Austrian Standards International, https://www.austrian-standards.at/de/shop/onorm-b-1600-2023-05-01~p2660558, 2023.

Statistik Graz: Bevölkerung, Bezirke, Wirtschaft, Geografie, https://www.graz.at/cms/beitrag/10034466/7772565/Zahlen_Fakten_Bevoelkerung_Bezirke_Wirtschaft.html, (Accessed on 16/04/2026).

Tannert, B. and Schöning, J.: Disabled, but at what cost? An examination of wheelchair routing algorithms, MobileHCI 2018 - Beyond Mobile: The Next 20 Years - 20th International Conference on Human-Computer Interaction with Mobile Devices and Services, Conference Proceedings, https://doi.org/10.1145/3229434.3229458, 2018.

Vestena, K., Camboim, S., and Santos, D.: OSM Sidewalkreator - A QGIS plugin for automated sidewalk drawing for OSM, in: Proceedings of the Academic Track at State of the Map 2022, edited by Minghini, M., Liu, P., Li, H., Grinberger, A. Y., and Juhász, L., Florence, Italy, https://doi.org/10.5281/zenodo.7004523, 2022.

Zipf, A., Mobasheri, A., Rousell, A., and Hahmann, S.: Crowdsourcing for individual needs – the case of routing and navigation for mobility-impaired persons, in: European Handbook of Crowdsourced Geographic Information, pp. 325–337, Ubiquity Press, https://doi.org/10.5334/bax.x, 2016.