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Design and implementation of a spatial database for analysis of wheelchair accessibility

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Abstract

Accessibility is an essential consideration in the design of public spaces, and commonly referred to as 'pedestrian accessibility' when walking is the primary mode of transportation. Computational methods, frequently coupled with Geographic Information systems (GIS), are increasingly available for assessing pedestrian accessibility using digital cartographic data such as road networks and digital terrain models. However, they often implicitly assume a level of mobility that may not be achievable by individuals with mobility impairments, e.g., wheelchair users. Therefore, it remains uncertain whether conventional pedestrian accessibility adequately approximates 'wheelchair accessibility,' and, if not, what computational resources would be required to evaluate it more accurately. We therefore designed a spatial database aimed at customizing mobility networks according to mobility limitations and compared the accessibility of a university campus for people with and without wheelchairs under various assumptions. The results showed there are clusters of locations either completely inaccessible or substantially less accessible for wheelchair users, indicating the presence of particular 'wheelchair coldspots', not only due to steep slopes and stairways but also arising from unforeseen consequences of aesthetic and safety enhancements, such as pebble pavements and raised sidewalks. It was found that a combination of simple spatial queries would help identifying potential locations for mobility aids such as ramps. These findings suggest that accessibility is not an invariant of a public space but experienced differently by different groups. Therefore, more comprehensive needs analysis and spatial database design are necessary to support inclusive design of healthier public spaces.

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Key words: accessibility, wheelchair, urban design, spatial database, geographic information systems (GIS).

Conflict of interest: the authors declare no potential conflict of interest, and all authors confirm accuracy.

Availability of data and materials: all data generated or analyzed during this study are included in this published article.

Acknowledgements: this work was supported by the Swedish Research Council Formas under Grant 2021-01867.

Received: 22 June 2024.
Accepted: 8 December 2024.

Geospatial Health 2025; 20:1324
doi:10.4081/gh.2025.1324

Introduction

Pedestrian accessibility—defined as "the ease with which certain destinations can be reached by walking" (Jehle *et al.*, 2022)—is a fundamental aspect of public space in cities and an intersection of the fields of urban design and health. For example, Hematian and Ranjbar (2022) examined the effects of urban elements as well as of walking in urban environments on mental health by comparing pedestrian and car-dominated streets, while Howell and Booth (2022) investigated the relationship between the built environment and metabolic health, promoting walkable and activity-friendly community designs mitigating the rise in obesity and diabetes prevalence. The United Nations (2015) recognizes walking as a sustainable mode of urban mobility as part of Goal 3 "Good Health and Well-being" and Goal 11 "Sustainable Cities and Communities" of its Sustainable Development Goals (SDGs). These goals underscore the potential contribution of pedestrian-accessible urban spaces to both public and individuals' health.

Computational methods have been developed for assessing pedestrian accessibility and becoming increasingly accessible to contemporary urban planners, thanks to advancements in spatial information technology as discussed by Merlin and Jehle (2023). Geographic Information Systems (GIS) assist the compiling of digital cartographic data, including details such as roads, landmarks, and places of interest, from various sources (Liu *et al.*, 2021) and are useful for calculating travel distance, time and energy (Páez *et al.*, 2020) as well as for visualizing spatial variations in them (Schöttler *et al.*, 2021). GIS applications often implicitly assume a certain level of mobility that may not be achievable by all citizens who require daily access to various facilities, services, and opportunities. In striving for a fair and inclusive society, it is essential to consider a wide range of citizen groups with varying levels of mobility, often limited by different types of impairments – including visual and hearing impairments as well as mobility impairments – when developing policies aimed at improving quality of life in urban areas.

The term 'pedestrian' needs to reflect the awareness mentioned above. For example, Lo (2009) promotes a more inclusive definition of pedestrians that includes those using wheelchairs or other aids in order to better understand and assess the walkability of urban spaces. In their glossary of sustainable transportation terms, Byars *et al.* (2017) define pedestrians as "persons walking, skateboarding, using a wheelchair or other mobility device or any other form of human-powered transportation other than a bicycle". They also include motorized wheelchair users in this definition. Furthermore, legal frameworks, such as the European Union's Regulation No 78/2009 (European Parliament, 2009), the United States Disabilities Act of 1990 (ADA, 1990) and Australia's Disability Discrimination Act of 1992 (DDA, 1992) recognize wheelchair users as legitimate pedestrians.

The inclusion of wheelchairs as a vital means of urban mobility revises pedestrian accessibility with an explicit consideration of topography and pathway structure, which literally adds a new dimension to accessibility analysis. While it is evident that man-made structures, such as stairways, curbs and uneven surfaces pose potential obstructions for wheelchairs (see Meyers *et al.* 2002 for a list of barriers for wheelchair users and Kapsalis *et al.* 2024 for illustrative graphics), the effect of gravity is of equally important with regard to the performance of wheelchairs in terms of downhill stability (Brubaker *et al.*, 1986; Thomas *et al.,* 2018) and energy expenditure (Nightingale *et al.*, 2017; Popp *et al.*, 2018). On the other hand, the careful design of sidewalks, road surfaces, and mobility aids such as ramps and dropped curbs can enhance wheelchair mobility (Long, 2020; Flemmer, 2022). When these additional factors are taken into account, "wheelchair accessibility" (Sahoo & Choudhury, 2023) may be a better term than pedestrian accessibility. However, it remains uncertain whether wheelchair accessibility can be approximated by pedestrian accessibility; if not, it needs to be decided which computational resources, including data and tools would be necessary for its evaluation. Wheelchair users are the specific focus of this paper, and we aimed to explore the potential of a computational method for a more inclusive analysis of pedestrian accessibility. To this end, we designed a spatial database for data storage of topography and basic mobility infrastructure, as well as mobility obstructions and aids. These data were processed to customize mobility networks according to individuals' needs and restrictions. Subsequently, we implemented a prototype of the spatial database and assessed its utility by comparing wheelchair accessibility and (conventional) pedestrian accessibility. Given the expectation that wheelchair accessibility is generally lower than pedestrian accessibility, we focused on identifying places that are completely inaccessible or substantially less accessible for wheelchair users. Additionally, we wished to demonstrate the capability of the database in explaining the causes of these conditions and devising their resolutions.

Materials and Methods

The design of a spatial database is described in terms of types of geometry and attributes to be stored, retrieved and processed to enable customization of mobility networks and evaluation of accessibility. A prototype was implemented for the main campus of a university, the Royal Institute of Technology (KTH), in Stockholm, Sweden (Figure 1) using commercial GIS software

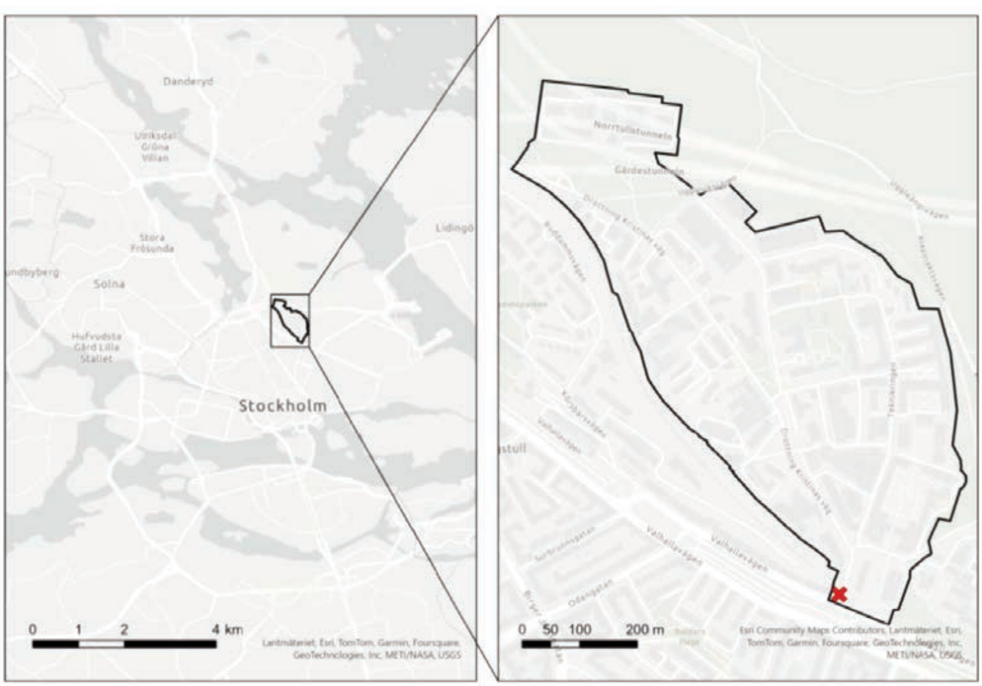

Figure 1. Study area encompassing the KTH campus (outlined by a solid line) with the main entrance of a subway station marked by a crosshair.

(ArcGIS and QGIS). The campus covers an area of 0.33 km² extending 900 m north to south and 800 m east to west, with an undulating topography of elevations ranging from 18.45 to 43.95 m. It is well-connected through sidewalks, stairways and ramps with different surface types such as asphalt, grass, dirt or stone.

Geometry of data

GIS data are typically organized in terms of layers—a layer being a set of spatial units that share the same geometric type and are characterized by the same set of attributes. Assuming that mobility is restricted to roads on Earth's surface, the database initially stores two layers: a road layer and an elevation layer. The road layer comprises polylines, each of which is a sequence of line segments starting and ending with nodes. While polylines represent road segments, nodes represents point features such as intersections or dead ends. The elevation layer is structured in raster format consisting of a grid of pixels. Each cell's location is uniquely identified by its corresponding row and column, with height (elevation) indicated by its associated value.

Data attributes

As summarized in Table 1, the road layer has at least 10 attributes: ID, NODE1, NODE2, LENGTH, ROAD TYPE, SURFACE TYPE, AID, SLOPE, CURB HEIGHT1, and CURB HEIGHT2. The ID attribute uniquely identifies each road segment (represented by a polyline) with an integer value, while NODE1 and NODE2 attributes uniquely identifies the two nodes of each road segment with integer values. The LENGTH attribute records the length of each road segment with a double value. The ROAD TYPE attribute describes the use or structure of each road segment with a string of letters, and the SURFACE TYPE attribute specifies the material or texture of each road segment using a string of letters. The AID attribute describes the mobility aid, such as ramp (if available) on each road segment with a string of letters. The slope attribute represents the slope of each road segment with a double value. Finally, the CURB HEIGHT1 and CURB HEIGHT2 attributes record the height of the curb at the first and second node, respectively, of each road segment.

Data acquisition

We obtained the geometry of a road layer within the KTH campus and some of its attributes from OpenStreetMap (OSM) (https://www.openstreetmap.org/). Initially, the data were encoded in GeoJSON format and exhibited topological inconsistencies, notably gaps between some supposedly connected polylines. We rectified these topological errors by converting the GeoJSON data

Figure 2. Sett (left) and cobblestone (right) surfaces types.

Table 1. Attributes of the road layer.

Term used	Data type	Description
ID	integer	Unique identifier of the road segment
NODE1	integer	Unique identifier of the first node of the road segment
NODE2	integer	Unique identifier of the second node of the road segment
LENGTH	double	Length of the road segment measured in meters
SURFACE TYPE	string	Material or texture of the surface of the road segment
ROAD TYPE	string	Use or structure of the road segment
AID	string	Mobility aid available on the road segment
SLOPE	double	Maximum slope along the road segment measured in percent
CURB HEIGHT1	double	Curb height at the first node of the road segment measured in millimeters
CURB HEIGHT2	double	Curb height at the second node of the road segment measured in millimeters

into a polyline layer encoded in ESRI (Redlands, CA, USA) shapefile format. We acquired a digital terrain model (DTM), which is a raster layer representing topographic height, of the KTH campus with a 2-m resolution from the Swedish Mapping, Cadastral and Land Registration Authority. We converted it into a raster layer encoded in ESRI's grid format.

Revision of attributes

All the attributes of the road layer except ID were initially unavailable, inaccurate or incomplete. We rectified them by generating unique identifiers for each node, populating the NODE1 and NODE2 attributes accordingly. The LENGTH attribute required recalculation, since the coordinate data were modified in the previous step to correct topological errors, while the SURFACE TYPE and ROAD TYPE attributes required validation and modification. This was primarily due to the lack of sufficiently detailed classification in the original data. For example, Figure 2 displays two types of road surface, which were both classified as 'paving stones' in the original OSM data but here distinguished as 'flat stones' and 'cobblestones' because they may pose different levels of difficulty for wheelchair users to traverse.

We conducted an on-site inspection of the KTH campus, making necessary changes to the SURFACE TYPE and ROAD TYPE attributes, on 3 November 2023 for approximately six hours. During this inspection, we also identified ramps as the sole type of mobility aid within the study area and updated the AID attribute accordingly. Upon completion of the inspection, the SURFACE TYPE attribute includes nine values: asphalt, concrete, slab, metal, wood, dirt, gravel, flat stones and cobblestone. The ROAD TYPE attribute included eight values: sidewalk, pavement (for pedestrian use), path (for non-vehicular use within open spaces such as squares, parks and forests), residential (for entry to on-campus apartments), service (for vehicular delivery and other services), local (for light vehicular traffic), stairway and motorway.

The SLOPE attribute was derived using the road layer and the elevation layer. As shown in Figure 3, each polyline was first segmented by placing points at approximately equal intervals of 2 meters that match the elevation layer's resolution. Then, the slope of each segment was calculated by first extracting the elevation values of the cells containing the two defining points of that segment and then dividing their difference by the length of that segment. The maximum slope among these segments was then stored in the SLOPE attribute.

The calculation of the CURB HEIGHT1 and CURB HEIGHT2 attributes utilized another polyline layer, where each polyline represents a curb segment of a constant height, potentially acting as a barrier for wheelchairs. This layer has only two attributes: ID and height, the former of which uniquely identifies each curb segment, while the latter indicates the height of each curb segment. We collected curb locations within the KTH campus using a GPS receiver and manually measured their heights, which were then converted into a polyline layer encoded in shapefile format. Subsequently, the CURB HEIGHT1 and CURB HEIGHT2 of each polyline were determined by intersecting the road layer with the curb layer (Figure 4).

Creation of mobility networks

We converted a road layer into a pedestrian network, which is composed of directed polylines referred to as 'arcs,' segmented by two nodes. Each arc represents a length and direction of movement from one node to the other. Pedestrians were assumed capable of traversing all roads except local roads (accompanied by sidewalks) and motorways (beneath the campus), and thus, polylines labelled as 'local' or 'motorway' were filtered out from the road layer. Subsequently, a node was created where two polylines intersected, and for each polyline, two arcs of opposite directions were created to represent bidirectional pedestrian movements.

Next, we constructed a wheelchair network as a subset of the pedestrian network based on five assumptions regarding wheelchair mobility outlined below. Each mobility assumption was defined by four parameters: traversable road type, traversable surface type, maximum traversable slope and maximum traversable curb height. In this case study, including all five assumptions, the traversable road type comprised all road types except 'local,' 'stairway' and

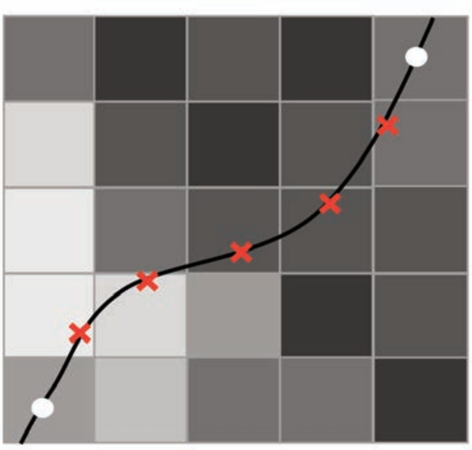

Figure 3. A polyline (connecting two dots) of the road layer overlaid on the elevation layer (with darker shades representing higher cells) and segmented by points (crosshairs) placed at approximately equal 2-m intervals.

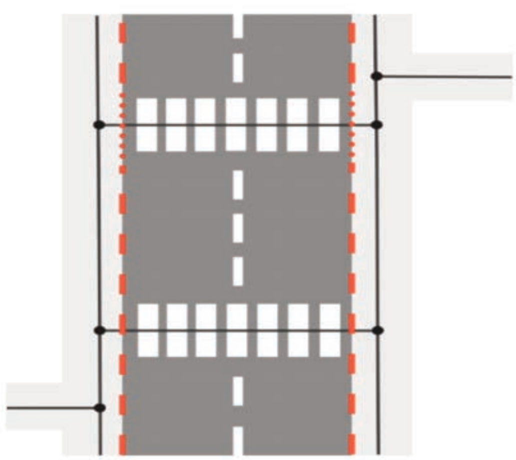

Figure 4. Curb segments of two different heights (dashed and dotted polylines) and road segments (solid polylines) with a background illustration of roads and crossings.

'motorway,' with the maximum traversable curb height was set to 5 cm. While we did not establish definitive boundary values for certain parameters, the parameter values defining the present wheelchair mobility assumptions were based on our interpretation of existing international standards, guidelines and studies conducted in the context of wheelchair use. For example, Assumption 1, which represents the lowest level of wheelchair mobility, employs a maximum traversable slope of 1:8, which corresponds to the slope regarded as manageable for short distances under the Americans with Disabilities Act (ADA, 1990). Other slope thresholds were selected based on the study by Lenker *et al.* (2016) on the usability of access ramps for both manual and power wheelchair users. Regarding surface types, dirt was considered easier to traverse than gravel or cobblestones due to its typically compacted and consistent nature. In contrast, gravel and cobblestones pose greater challenges because their loose or uneven surfaces increase rolling resistance and instability for wheelchairs (Cooper et al., 2012). Additionally, the maximum curb height of 5 cm adhered to the International Standard Organization (ISO) standards no. 21542:2021 (ISO, 2021) for step-free access, ensuring practical usability in real-world scenarios. The resulting assumptions are listed in Table 2. Finally, for each assumption, a wheelchair network was derived from the pedestrian network by selecting only traversable arcs. In total, five mobility networks were stored in the database, comprising one pedestrian network and five wheelchair networks.

Evaluation of accessibility

We evaluated the accessibility of each node in every mobility network by measuring its travel distance from the main entrance of a subway station (marked by the crosshairs in Figure 1). This entrance was also located several meters away from a train station and a bus terminal establishing it as the primary entry point to the KTH campus. Therefore, we designated it as the network origin. However, we acknowledge that a more comprehensive analysis, though computationally more complex, would require considering every node as a potential origin. In travel distance measurement, the shortest path algorithm according to Dijkstra (1959) was applied to each mobility network generated earlier to compute the shortest paths from the origin to all nodes. These paths collectively form a tree and are therefore termed the 'shortest path tree.' Specifically, the one produced on a pedestrian network was referred to as the 'pedestrian shortest path tree,' while the one generated on a wheelchair network as the 'wheelchair shortest path tree.' Each such tree was stored in the database by recording, for each node, its distance from the origin (referred to as its 'shortest path distance') and the node that preceded it in its associated shortest path (referred to as its 'previous node'). In total, six shortest path trees were stored in the database, including one pedestrian shortest path tree and five wheelchair shortest path trees.

Identification of wheelchair coldspots and causes

In each pair of shortest path trees generated in the previous step, we calculated the ratio of wheelchair distance to pedestrian distance for every node, termed as 'relative wheelchair accessibility.' A higher value of this measure indicates decreasing accessibility for wheelchair users at the corresponding node. A higher value of this measure indicates that the corresponding node is less accessible to wheelchair users. Furthermore, we performed spatial queries on the two shortest path trees to find where the wheelchair shortest path tree diverges from the pedestrian shortest path tree, as illustrated in Figure 5. The specific query conditions were to select

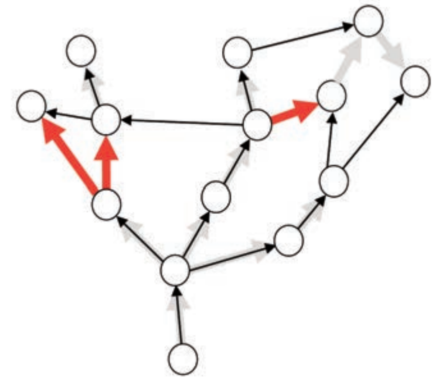

Figure 5. Bottleneck arcs (in red) where the wheelchair shortest path tree (thin arrows) fail to follow the pedestrian shortest path tree (thick arrows).

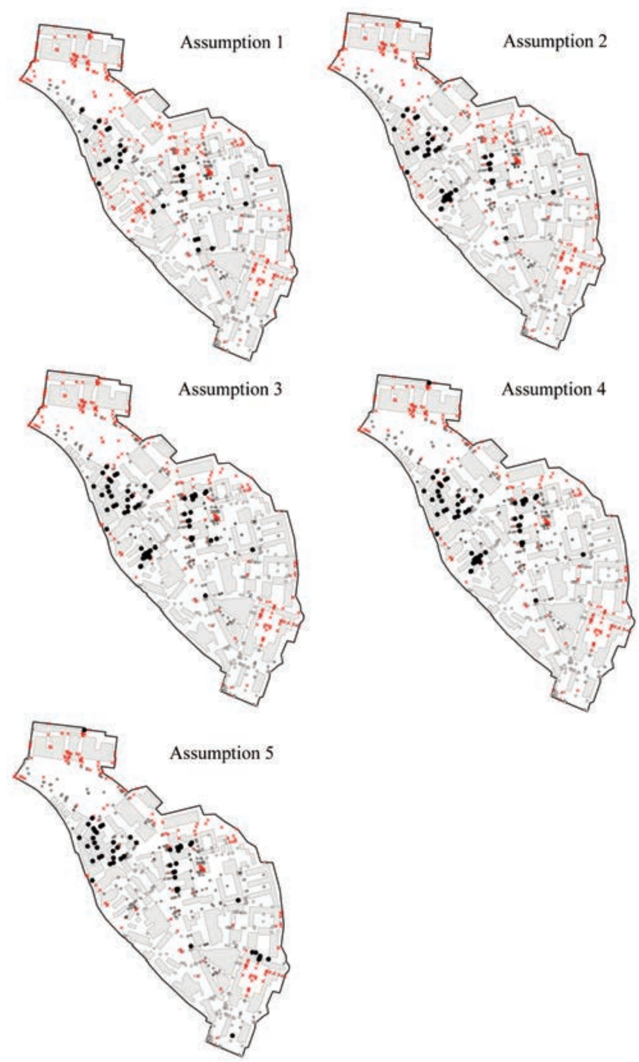

Figure 6 Wheelchair cold spots in the KTH campus. The crosshairs (in red) indicate completely inaccessible nodes, while the dots (in black) indicate substantially less accessible nodes. Each map corresponds to one of the six wheelchair mobility assumptions.

arcs that: i) were included in the pedestrian shortest path tree; ii) were not included in the wheelchair shortest path tree; and iii) followed arcs included in both trees. These arcs served as bottlenecks to wheelchair accessibility. We analyzed their attributes to identify barriers hindering wheelchair users from utilizing them and explored possible solutions to eliminate these barriers.

Results

Mobility networks

The data collected for the accessibility analysis of the KTH campus comprising 763 polylines delimited by 584 nodes were compiled into the road layer. These elements are uniquely identified by the ID attribute and by the NODE1 and NODE2 attributes, respectively. The LENGTH attribute ranges from 0.37 m to 225.8 m. In the AID attribute, six of the 763 polylines are labeled as 'ramps,' while the remaining polylines have no assigned values, indicating no designated mobility aids. The distributions of values for the ROAD TYPE, SURFACE TYPE, SLOPE and CURB HEIGHT (1 & 2) attributes are summarized in Table 3.

The road layer was then converted into a pedestrian network, as well as five wheelchair networks, each corresponding to one of the five assumptions regarding wheelchair mobility. The pedestrian network comprises 584 nodes and 1,526 (=763·2) arcs. The five wheelchair networks share the same set of nodes as the pedestrian network, but have fewer arcs—850 (=425·2); 902 (= 451·2); 954 (= 477·2); 1024 (= 512·2); and 1,060 (= 530·2) arcs for the five different assumptions (in ascending order with respect to ease of mobility), respectively.

Analysis of wheelchair accessibility

The relative wheelchair accessibility of each node was calculated under each of the five wheelchair mobility assumptions (see Table 4 for their distribution). Nodes without paths from the origin were assigned the value 'undefined' and labelled as completely

Table 2. Five parametric assumptions on wheelchair mobility.

Assumption	Traversable road type	Traversable surface type	Maximum traversable slope	Maximum traversable curb height
1	All except local, stairway and motorway	All except dirt, gravel and cobblestone	1:8	5 cm
2	All except local, stairway and motorway	All except dirt, gravel and cobblestone	1:6	5 cm
3	All except local, stairway and motorway	All except dirt, gravel and cobblestone	1:4	5 cm
4	All except local, stairway and motorway	All except dirt, gravel and cobblestone	1:4	5 cm
5	All except local, stairway and motorway	All except dirt, gravel and cobblestone	1:3	5 cm

Data presented in descending order of wheelchair mobility with Assumption 1 representing the lowest wheelchair mobility.

Table 3. Distributions the road layer's attributes values.

Road type	Pavement	Sidewalk	Path	Residential	Service	Local	Stairway	Motorway	Total	
Count	347	80	54	13	152	49	60	8	763	
Surface type	**Asphalt**	**Concrete**	**Slabs**	**Metal**	**Wood**	**Flat stones**	**Dirt**	**Gravel**	**Cobble-stones**	**Total**
Count	414	27	112	1	2	97	48	26	36	763
Curb height	**No curb**	**2 cm**	**3 cm**	**4 cm**	**7 cm**	**10 cm**	**12 cm**	**Total**		
Count	700	3	3	2	1	17	37	763		
Slope	**< 1:20**	**1:20-1:12**	**1:12-1:8**	**1:8-1:6**	**1:6-1:4**	**1:4-1:3**	**> 1:3**	**Total**		
Count	298	178	108	49	57	42	31	763		

Curb height indicates the maximum of Curb height 1 and Curb height 2 values for each polyline.

Table 4. Distributions of relative wheelchair accessibility values under the five wheelchair mobility assumptions.

	Relative wheelchair accessibility value						
Assumption	1	1-1.2	1.2-1.4	1.4-1.6	1.6-1.8	1.8-2.0	Undefined
1	137	127	14	4	9	8	285
2	163	139	21	5	11	5	240
3	174	139	32	10	11	5	213
4	174	164	31	10	11	5	189
5	176	180	24	12	11	5	176

The undefined column represents the number of nodes completely inaccessible to wheelchair users.

inaccessible, while nodes with values greater than 1.2 (selected arbitrarily for demonstration purposes) were labelled substantially less accessible for wheelchair users. These nodes are identified as ‘wheelchair cold spots,’ and their locations are depicted in Figure 6. For each wheelchair mobility assumption, all arcs meeting the query conditions were selected. These arcs, not used by wheelchair users in their shortest path routes, are potential bottlenecks for wheelchair accessibility. As summarized in Table 5, they are considered untraversable due to one or more of their attributes.

The spatial distribution of wheelchair coldspots in Figure 5, along with their attributes in Table 5, suggest potential structural modifications to enhance wheelchair accessibility. For instance, under Assumption 3, there is a cluster of 57 completely inaccessible nodes in the northern part of the study area. This may be attributed to a single bottleneck arc having a high curb (Figure 7,1). Lowering that curb could eliminate 21 of them. Similarly, within the same assumption, a cluster of 13 substantially less accessible nodes near the left-centre of the study area is caused by a single bottleneck arc labelled as ‘stairway’ (Figure 7,2). This cluster could be completely resolved by installing a ramp.

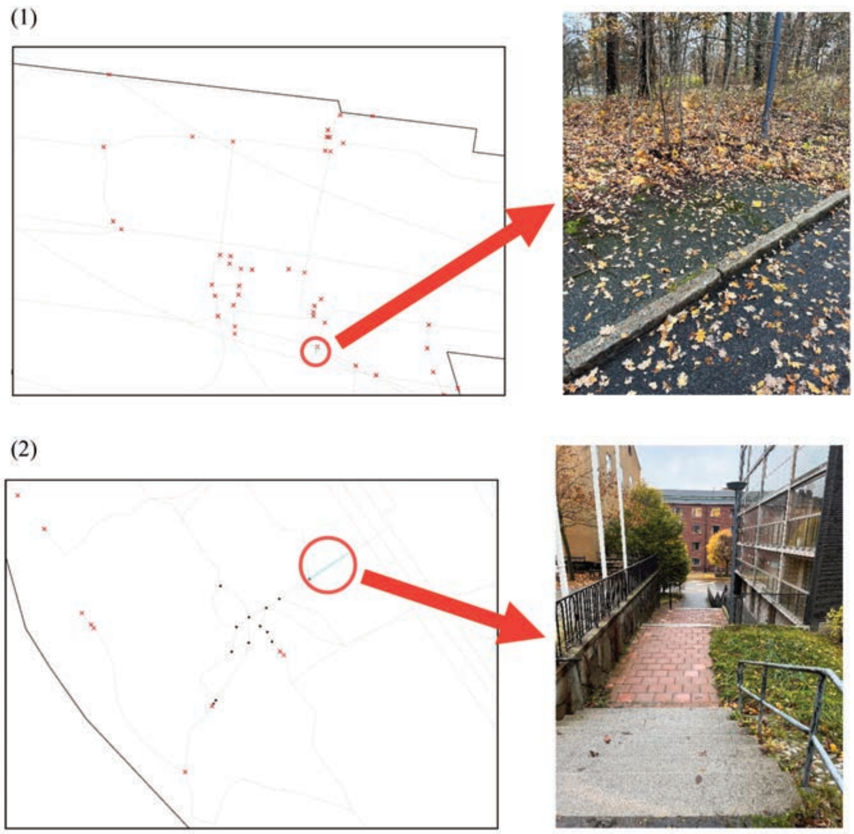

Figure 7. Bottleneck arcs (highlighted in blue and enclosed by a circle) causing (1) a cluster of completely inaccessible nodes (crosshairs) in the northern part of the study area and (2) a cluster of substantially less accessible nodes (dots) in the left-centre part of the study area, along with images of their corresponding obstacles: high curb and a stairway, respectively (as indicated by arrows).

Table 5. Distribution of bottleneck arcs by causal attribute.

Assumption	Surface type	Curb height	Slope	Road type	Total
1	11	25	46	21	87
2	12	34	40	23	96
3	13	34	30	26	93
4	9	34	34	26	95
5	10	35	18	26	89

For each assumption, the sum of the number of bottleneck arcs caused by each attribute (from 2nd to 5th column) may not match the total number of bottleneck arcs (last column) as some bottleneck arcs were caused by more than one attribute.

Discussion

Results of the case study provide valuable insights into the design, implementation, and use of our spatial database for analyzing the accessibility of public spaces for wheelchair users. This section discusses key findings and their implications, highlighting both merits and limitations of the database, and suggests future research directions for its improvement.

Flexible and inclusive accessibility analysis

It was found that wheelchair users have disproportionately lower accessibility than (other) pedestrians within the outdoor KTH campus. For instance, under Assumption 3—the most realistic of the five assumptions employed in the case study—more than one-third of all campus nodes were deemed completely inaccessible, with 10% substantially less accessible for wheelchair users. These nodes, termed 'wheelchair coldspots,' effectively pinpoint areas with "inequities and substandard conditions" (Handy & Niemeier 1997, p. 1176). We devised 'relative wheelchair accessibility' to measure wheelchair-pedestrian inequality. However, this ratio increases as the assumed mobility of wheelchair users becomes more restricted (see Table 4). This finding aligns with the observation that wheelchair accessibility is generally lower than pedestrian accessibility as certain road objects or conditions may pose barriers to wheelchair users but not to pedestrians. However, these barriers are not necessarily "absolute" (Meyers *et al.*, 2002) but may be perceived or experienced differently by individual wheelchair users. Importantly, our database allowed the application of different mobility assumptions to accessibility analysis with ease, without rebuilding the underlying accessibility model or revising relevant mobility data.

The visual inspection of the locations of wheelchair coldspots (Figure 6) identified clusters and suggested that some of these clusters might be caused by a few road segments serving as bottlenecks. In fact, as illustrated in Figure 5, a simple spatial query in our database effectively retrieved potential bottleneck road segments. Structural modifications, such as installing ramps, lowering curbs or redesigning pathways, may be necessary to eliminate these bottlenecks and enhance wheelchair accessibility. The combination of standard GIS functions for spatial data visualization and querying provided quick initial insights into where such structural modifications may be needed (Figure 7). It is important to note that not all mobility barriers necessarily function as bottlenecks. While removing all barriers might be ideal, it may not be realistic, at least in the short term due to limited budgets and conflicting interests, as is often the case with public space improvements (Bromley *et al*., 2007; Flemmer, 2022). Our database helps plan the efficient investment of resources by distinguishing between mobility barriers that degrade overall accessibility and those that cause localized inconveniences

Ironically, some physical structures intended to improve pedestrian safety (*e.g*., curbs separating pedestrian lanes from vehicle lanes) were found to reduce wheelchair accessibility. This finding aligns with the observations by Pérez-del Hoyo *et al.*, (2019) that accessibility issues arise not only from well-known obstacles like steep slopes but also from unexpected consequences of aesthetic and safety enhancements. While the dual (positive and negative) impacts of mobility infrastructure present a challenge to urban designers, they also provide an opportunity for our spatial database to offer a holistic and inclusive perspective in the design of public spaces.

The current approach to measuring accessibility in terms of travel distance, while convertible to travel time (see Arai *et al.*, 2022, for a formula for the travel time of each arc of a pedestrian network in a station), may not comprehensively capture the practical challenges faced by wheelchair users in navigating real-world environments (Sahoo & Choudhury, 2023). One potential alternative to distance or time is energy consumption (Cooper *et al.*, 1995). It is important to note that estimating the energy or work required by a wheelchair to travel is direction-dependent. To see this clearly, consider a road segment on an undulating surface: ascending will inevitably demand more energy (and thus more work or battery) than descending on the same segment. Thus, unlike length, two arcs of opposite direction derived from a road segment may well have different energy values due to positive and height differences. Fortunately, our spatial database was designed to store such direction-dependent information. For example, the signed height difference or slope can be readily retrieved, as the corresponding two nodes are already individually indexed in the NODE 1 and NODE 2 attributes, and their heights can be stored in additional attributes like ELEVATION 1 and ELEVATION 2. A similar technique was used to store the curb height for each end of a road segment (see Table 1). This capability to manage direction-dependent data should be considered a strength of our database.

Limitations and future improvements

The scope of the study, both geographic and thematic, was admittedly limited. In larger public spaces, while the design and use of the spatial database might remain the same, its implementation would require additional effort and cost, particularly for the collection, verification, and modification of relevant data. An additional limitation was the sole reliance on distance as the measure of accessibility. In some contexts, factors like time and energy may be equally or even more important, which necessitate data and evaluation methods that account for directionality. The spatial database presented already has mechanisms to store direction-sensitive data, but it would still be necessary to incorporate computational models to convert such data into accessibility measures. With this improvement, the method could be adapted to analyze accessibility for additional modes of mobility such as biking and scooting (with or without battery assistance). This highlights the potential of the proposed method to achieve greater flexibility and inclusivity in accessibility analysis, which, in turn, would contribute to creating healthier and more welcoming urban environments. Our current parametric design of mobility assumptions was another notable limitation, which may not fully encompass the complexities of real-world scenarios for wheelchair users. Conditions can vary widely, and individuals' abilities to navigate terrain depend on factors such as wheelchair type (Da Silva Bertolaccini *et al.*, 2022), physical strength (Ambrosio *et al.*, 2005) and mobility skills and exercise training (Sol *et al*., 2021). Additionally, our model considers only a few parameters, such as road type, surface type, slope, and curb height. However, other significant factors, such as weather conditions (Borisoff *et al.*, 2018), the presence of obstacles (Henje *et al.*, 2021) and pedestrian traffic flow (Wu *et al.*, 2022), should also impact wheelchair accessibility. Future work could expand the mobility assumptions and test them directly with wheelchair users to ensure their validity and relevance. Engaging users in real-world trials would provide valuable insights into the interactions among wheelchair types, environmental conditions, and personal capabilities. For instance, controlled experiments or surveys with wheelchair users could assess the traversability of specific slopes or surfaces under varied conditions. Such user-centered validation would enhance the accuracy of the assumptions and refine the spatial database to better reflect the lived experiences of individuals with mobility restrictions. These examples suggest that the primary use of the current spatial database is to support the initial exploratory stages of public space improvement by enabling urban designers to view public spaces from various perspectives and promptly identify potential mobility issues and solutions for a broad range of mobility restrictions.

The case study has also identified some concerns in the current implementation of the spatial database. One primary one lies in the availability and quality of the data, including the road layer obtained from OSM as a base dataset. While OSM is known for offering a wealth of geographic data free of charge, it is important to acknowledge the inherent limitations of volunteered data sources in terms of accuracy and completeness (Haklay, 2010; Goodchild & Li, 2012). These limitations often arise with data of a “microgeographic” nature (Lesbegueries *et al.*, 2012) such as curb heights or surface types. Implementing the database for our study area necessitated a comprehensive tour of a university campus for on-site validation and rectification of road attributes. This raises questions about the scalability of the spatial database. While feasible for relatively small public spaces like a university campus, this approach would be prohibitively labour-intensive and impractical for larger areas. The adoption of new data collection technologies is essential to make the proposed approach scalable. For instance, Kasemsuppakorn and Karimi (2013) and Yang *et al.* (2019) each created pedestrian networks from shared/crowd-sourced GPS-tracking data, offering a potential solution to scale up accessibility analysis. More recently, Fernández-Arango *et al.* (2022) presented a method for creating three-dimensional models of road surfaces comprising elements such as curbs, benches, lampposts and trees from point clouds collected with a mobile Light Detection and Ranging (LiDAR) scanner to model pedestrian mobility. Future studies should explore how these emerging geospatial technologies can be leveraged to automate data collection for modelling the mobility patterns of various pedestrian types, including wheelchair users.

Conclusions

This study investigated the prospect of a computational method for more flexible and inclusive accessibility analysis in urban public spaces where walking is considered the primary mode of mobility. It relies on a spatial database containing layers of geographic data on fundamental mobility infrastructure, as well as obstacles and aids to mobility. Equipped with capabilities for geometric computation and spatial query, the database can generate various mobility networks tailored to particular physical needs and limitations of pedestrians, including wheelchair users. We implemented a prototype of this spatial database for a university campus using commercial GIS software. The accessibility for wheelchair users was measured in terms of shortest path distance and compared with that for pedestrians without mobility aids across five different assumptions regarding wheelchair mobility. Clusters of ‘wheelchair coldspots’ were identified, consisting of completely inaccessible nodes and substantially less accessible nodes for wheelchair users. Analysis revealed that several road segments with inhospitable surfaces, steep slopes, and high curbs were contributing to these clusters, suggesting that addressing these issues could enhance wheelchair accessibility on campus.

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