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Simulating and visualizing sidewalk accessibility for wayfinding of people with disabilities

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ABSTRACT
There are generally different and less wayfinding options for pedestrians than those for drivers. This makes developing models and tools that assist pedestrians in finding routes more challenging. The problem is even further exacerbated when specific routing requirements of people with disabilities are considered. While currently much research is focused on developing solutions for wayfinding of pedestrians, very few address the specific requirements of individuals with disabilities and none is focused on evaluation of the accessibility of built environments. In this paper, we propose a new approach in evaluating the accessibility of built environments for wayfinding of individuals with disabilities. The proposed approach involves simulation and visualization of the accessibility of sidewalk segments allowing urban planners, and other designers and engineers, to gain an understanding of how accessible built environments are and allowing individuals with disabilities to assess the accessibility of built environments with respect to their mobility needs. Simulations were conducted using a sidewalk network database which contains accessibility attributes based on the standards recommended by the Americans with Disabilities Act. To demonstrate the benefits of the proposed approach, a representative model was used to simulate scenarios for the wayfinding requirements at both community and individual levels. The results of the simulations are visualized in heat-maps.

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Accessibility of sidewalks; pedestrian wayfinding; wheelchair user wayfinding; blind or visually impaired wayfinding

Introduction

Planning how to get around on foot is an integral part of everyday life. While, nowadays, drivers can generally rely on vehicle navigation systems for their travel needs, pedestrians have far more complex requirements to fulfill (May, Ross, Bayer, & Tarkiainen, 2003; Millonig & Schechtner, 2007). The shortest path is not always optimal for an individual's purposes as people often prefer the most convenient, the safest or the most scenic path (Karimi, Jiang, & Zhu, 2013). Wayfinding, a process of determining and following a path or route between an origin and destination (Golledge & Reginald, 1999), becomes even more challenging for people with disabilities. For people with physical disabilities, even a short trip can be a

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daunting task and perhaps impossible to perform. People with physical disabilities encounter more barriers on sidewalks than others. For example, commuting in a crowded environment could be challenging for an individual who is blind or a wheelchair user. Obstacles such as stairs, no ramps or steep ramps, poor segment surface, no curb cuts or blocked curb cuts, make the sidewalks uncomfortable or even inaccessible to people with disabilities (Rimmer, Riley, Wang, Rauworth, & Jurkowski, 2004). In 1990, the US government recognized a need to define built environments to allow equal access to all people and passed the Americans with Disabilities Act (ADA). One main goal of the ADA is to provide people with disabilities access to buildings, access to public transportation and the opportunity to attend schools. Routing solutions that consider the accessibility of the built environment would help people with disabilities travel around more comfortably, have access to more public facilities and adopt more socially active life styles (Heath & Fentem, 1996).

In this paper, we present a new methodology for evaluating the accessibility of sidewalks for wayfinding of people with disabilities. The proposed methodology is performed through simulation and visualization. For demonstration purposes, we use a weighted linear model, which takes into account different characteristics of a sidewalk segment, for the simulation of accessibility. These characteristics, as the linear model parameters, were investigated by Kasemsuppakorn and Karimi (2008) and include segment slope, number of steps, segment distance, number of crosswalks, different traffic zones, surface type and condition, segment width and number of landmarks. The idea behind any model, such as the one used in this work, is to provide individuals with appropriate travel paths on a sidewalk network. To better understand the wayfinding issues and challenges with respect to accessibility of the built environment, the requirements of two groups of people with disabilities, wheelchair users and individuals who are blind or visually impaired (B/VI), were simulated. The sidewalk network of the University of Pittsburgh's main campus was used in the simulations and the results are presented through heat-maps which show the degree of comfort by each group on each sidewalk segment. The generated heat-maps also show that there are differences in paths desired by individuals in each group and in paths desired by both groups (we call each group a community).

The main research question that this paper aims to address is as follows: How can the accessibility of the built environment be evaluated for wayfinding by people with disabilities? The contribution of the paper is the evaluation of the built environment (sidewalk networks) through simulation and visualization of wayfinding of pedestrians with disabilities. Visualizing the results of simulations through heat-maps benefits urban planners and people with disabilities. Urban planners can evaluate the accessibility of the built environment and find the accessibility gaps, and people with disabilities can choose accessible routes that meet their needs and preferences. The structure of the paper is as follows. Background to wayfinding approaches and tools for people with disabilities is discussed in the 'Background' section. A representative model is described in the 'Model' section. The 'Simulation' section explains how the simulation is conducted. Simulation results are discussed in the 'Simulation Results' section. Finally, we will discuss summary and future work in the last section.

Background

There is a void in the literature about simulation and visualization of the accessibility of sidewalk segments specifically for wayfinding of people with disabilities. Our simulation and visualization approach is unique and will provide insights into new ways to evaluate the accessibility of urban areas. However, considering that people with disabilities are the major beneficiaries of the proposed simulation and visualization approach, in this section, selected existing wayfinding systems and services designed specifically for wheelchair users and people who are B/VI are discussed.

U-Access (Sobek & Miller, 2006) is a routing tool that provides pedestrians with the shortest feasible route with respect to one of the three different ability levels, namely peripatetic (unaided mobility), aided mobility (mobility with the help of a cane, walker or crutches) and wheelchair users. U-Access is also an analytical tool that can help identify obstacles in built environments and evaluate routing discrepancies among pedestrians with different physical abilities. Beale, Field, Briggs, Picton, and Matthews (2006) introduced a web-based navigation service with a user-friendly interface that considers impedances to accessibility for wheelchair users. It employs several criteria such as barriers, slope and challenging surfaces in addition to distance for wayfinding. Holone, Misund, and Holmstedt (2007) proposed a mobile route planning system, Ourway, based on user feedback. This pedestrian navigation tool provides special features for people with mobility impairments and the collaboration between users is in the form of shared experiences. Volker and Weber (2008) developed a system for collaborative multimodal annotation of geographical data and personalized routing of mobility impaired pedestrians. The system allows pedestrians to cooperate in collecting information about points of interest, environmental features such as slopes, locations of obstacles and images, as well as providing convenience and safety ratings. These data can then be shared among different groups anonymously. The system considers individual preferences and temporal relations of annotated data, in addition to the collected information by users, to calculate personalized multi-criteria routes for pedestrians with special needs including motor impaired, elderly people and people who are B/VI. Neis and Zielstra (2014) developed an algorithm for generating a sidewalk network for people with disabilities. They used the freely available data from the OpenStreetMap (OSM) project (Benner & Karimi, 2013) to obtain the required parameters for navigation of people with disabilities. The parameters included sidewalk width, slope, surface, smoothness, curb, lighting, tactile paving and steps. The resulting sidewalk network was overlaid on the OSM base map.

Karimi, Zhang, and Benner (2013) developed personalized accessibility map (PAM), an interactive map featuring accessibility data and specific functions suitable for people with special needs to assist them with their wayfinding needs and preferences. The benefits of PAM to people with disabilities, especially wheelchair users, were demonstrated through a prototype PAM for the University of Pittsburgh's main campus (PAM-Pitt). Users of PAM-Pitt can locate accessible entrances of campus buildings, find the shortest paths between campus buildings and request accessible paths between campus buildings based on their requirements and preferences. An accessible path for a wheelchair user is an example of the services offered by the PAM. The sidewalk network database in PAM-Pitt was manually collected by using various techniques and tools and taking into account the specific parameters of the ADA standards (Kasemsuppakorn & Karimi, 2008). The sidewalk network database in the PAM includes attributes such as sidewalk slope, surface condition, length, steps, width and traffic. To compute accessible paths for wheelchair users in the PAM, a fuzzy logic model developed by Kasemsuppakorn and Karimi (2009) is used. Kasemsuppakorn, Karimi, Ding, and Ojeda (2014) developed an algorithm, based on this model, and evaluated it by subjects (wheelchair users) within the University of Pittsburgh's main campus. The results of the evaluation indicate that wheelchair users may not be able to take the shortest path and prefer an accessible, and comfortable, path instead even if their travel distance and time are increased.

Wayfinding by individuals who are B/VI has been studied in some research projects. Petrie et al. (1996) presented a travel aid for the blind and elderly, built on geographic information systems and global positioning system (GPS) technologies. It consists of two components: the MOBIC Pre-journey System to assist users in planning journeys and the MOBIC Outdoor System to execute these plans by providing users with orientation and navigation assistance during journeys. The MOBIC travel aid is complementary to primary mobility aids such as the long cane or guide dog. The SmartVision project (Fernandes, du Buf, et al., 2011) presented a prototype addressing three main applications: (1) local navigation for centering on footpaths and obstacle avoidance, in the immediate surroundings, but just beyond the reach of the white cane; (2) global navigation for finding one's way and (3) object/obstacle recognition, not only on the shelves in a pantry or supermarket, but also outdoor such as bus stops, taxi stands, ATM machines and telephone booths. The Nav4B (Fernandes, Faria, Paredes, & Barroso, 2011) project aims to create a small, cheap and portable application as an extension of the work performed in the SmartVision project. The new prototype is built with the same modular structure as in SmartVision. Kammoun, Dramas, Oriolaand, and Jouffrais (2010) presented a method for finding optimal routes between pairs of origin and destination points for the individual who is blind, and used the proposed method in an assistive device for the blind, called NAVIG (Navigation Assisted by Artificial Vision and Global Navigation Satellite System). In their work, four main classes of objects including points of interest, landmarks, walking areas and visual points were annotated in the database. In order to calculate the cost of a link between two nodes in the graph, user profit and system profit, along with parameters such as sidewalk (presence and width), the presence of pedestrian crossing and length of a section were considered. User profit of a graph link depends on the presence of points of interest and landmarks, and system profit depends on the presence of visual points. The optimal route is computed by using Dijkstra's algorithm. A simulation and a prototype were designed to test the performance of the proposed algorithm.

There are also some products designed to assist people with B/VI. Trekker Breeze and Sense Nav are two examples of these products. The Trekker Breeze handheld talking GPS[1] can be controlled by one hand. It verbally announces names of streets, intersections and landmarks as the person walks and prevents the individuals who are B/VI from getting lost or missing a stop when traveling by bus. Sense Navigation (Sense Nav[2]) uses map data together with a GPS receiver and gives information based on the map data to the individual who is blind by means of voice and braille notes. Trekker and Sense Nav both use map data designed for car navigation.

It is clear from these selected projects that there is a void in the literature about evaluating the accessibility of the built environment through simulation and visualization of wayfinding of people with disabilities. In this work, we present a simulation methodology to evaluate the accessibility of the built environment. The methodology, which includes sidewalk data and routing models shows how the accessibility of sidewalks is simulated and visualized using any, existing or new, valid routing models.

Model

In this section, a representative model, to describe the methodology for simulating and visualizing the accessibility of the built environment, is presented. The model parameters are relevant sidewalk characteristics that are required by individuals who are wheelchair users or B/VI. It must be noted that while the use of a model in the methodology is needed for simulating wayfinding scenarios, finding a suitable model is a separate research and beyond the scope of this paper.

Wayfinding parameters

People with disabilities require specific requirements for traveling on sidewalks (Heath & Fentem, 1996; Karimi, Dias, Pearlman, & Zimmerman, 2014; Rimmer et al., 2004). Depending on the type of disability, they may need or prefer other requirements beside distance or trip duration. For example, wheelchair users may want to avoid sidewalks with steps or may prefer less steep walkways in case of manual wheelchairs, or an individual who is B/VI may want walkways with minimum crosswalks to avoid street crossings. Considering these requirements, different parameters for evaluating sidewalk segments can be involved in order to determine the degree of comfort for wheelchair users and individuals who are B/VI. One important parameter is sidewalk slope. According to the ADA standards and the U.S. Department of Justice,[3] sidewalk slope should not be greater than the 1:20 maximum. Another parameter is step, representing the number of sudden elevation on a sidewalk segment, as an impeding factor for wheelchair users. Furthermore, walkway surface condition also matters to pedestrians with wheelchairs. For example, a sidewalk surface with cracks makes it difficult for a wheelchair user to travel. Kasemsuppakorn and Karimi (2009) proposed Equation (1) to calculate the surface condition score.

$$\text{SidewalkConditionScore} = (3 \times \text{UnevenSurfaceScore}) + (2 \times \text{CracksScore}) + (\text{ManholeScore}). \quad (1)$$

This score is a combination of uneven surfaces, cracks and manholes on sidewalk segments. Equation (1) is one possible model for measuring sidewalk surface condition which shows the important parameters, how they are combined and how they could be weighted. Surface type, which is most often concrete, asphalt, brick, cobblestone, grass or gravel, is assigned a score between 1, for concrete, to 6, for gravel (Kasemsuppakorn & Karimi, 2009). The surface type score is combined with surface condition score to form the 'sidewalk surface' parameter. Width of sidewalk is another parameter for which the ADA standard recommendation is a minimum of 91.44 centimeters. Crosswalk is a parameter which mostly concerns individuals who are B/VI. Sidewalk traffic is also important because a crowded sidewalk slows down the movement of all pedestrians, in particular those who are B/VI and use wheelchairs. Number of landmarks along a route is another parameter, as usually landmarks assist people in finding their way, especially in unfamiliar environments.

Weighted linear model

Based on the sidewalk parameters discussed above, in this section, we present Equation (2) as a representative model for simulation. In this linear model, all parameters are weighted and averaged as one impedance score for each sidewalk segment. A segment impedance score determines its degree of comfort grouped into 'comfortable', 'semi-comfortable', 'uncomfortable', and 'impassable'. W1–W8 are the weights for the eight parameters in the equation. Each weight is assigned a discrete value between 1 and 6. Note that this range is only for experimentation in this work and a proper range may be determined through a focus group study or other approaches. The higher weight assigned to a parameter indicates a lower degree of comfort by the user for that parameter. For example, assigning a value of 6 to W1 in Equation (2) indicates that slope causes a high level of difficulty. With eight parameters and six possible values for each parameter, there are 6^8 possible combinations of weight assignments. This means that a segment can be assigned 6^8 different impedance scores, where its degree of comfort may be different from one score to another. These variations allow different users to evaluate the sidewalk network differently, depending on the combination of weights they choose for the relevant parameters.

$$\begin{aligned}\text{SegmentImpedanceScore} = {} & W1 \times \frac{\text{slope}}{\text{Max(slope)}} + W2 \times \frac{\text{steps}}{\text{Max(steps)}} \\ & + W3 \times \frac{\text{length}}{\text{Max(length)}} + W4 \times \frac{\text{crosswalk}}{\text{Max(crosswalk)}} + W5 \times \frac{\text{traffic}}{\text{Max(traffic)}} \\ & + W6 \times \frac{\text{surfacetype} + \text{surfacecondition}}{\text{Max(surfacetype} + \text{surfacecondition)}} \\ & + W7 \times \left(1 - \frac{\text{width}}{\text{Max(width)}}\right) + W8 \times \left(1 - \frac{\text{landmark}}{\text{Max(landmark)}}\right). \end{aligned} \tag{2}$$

In order to normalize the parameters of a sidewalk segment, the value of each parameter is divided by the maximum value possible for that parameter. For example, if the highest value of slope is 20 degrees in the sidewalk network under experiment, 20 is the maximum value of slope in the equation, although the maximum possible value for slope is 90 degrees. For calculating the surface parameter, we used the sum of surface type value and surface condition value of a segment. Surface type values ranges from 1, most convenient, to 6, least convenient. Surface condition value is zero in the absence of cracks, manholes and uneven surfaces, and increases as the condition of sidewalk surface degrades. For width and landmark parameters, instead of the normalized values, we considered 1 minus normalized value. The reason is that, unlike other parameters, higher values for width and number of landmarks make a sidewalk segment more comfortable.

It is important that the models expressed in Equations (1) and (2) be robust in unclear and uncertain situations. The sensitivity of these models can be analyzed for various arbitrary and uncertain values for each parameter and for each weight. Such a sensitivity analysis will make the model suitable for a variety of purposes and applications. For example, urban planners can analyze the degree of comfort of a sidewalk segment for a group of individuals with special needs. Another example is that individuals can analyze various segment impedance scores to find those that best suit their needs and preferences. In both examples, a range of uncertain values for the parameters and weights need to be considered. An interactive decision support system based on appropriate models, such as those in Equations (1) and (2), could be equipped with a highly interactive visualization tool to visualize the results of testing the robustness of the models (Andrienko & Andrienko, 2003).

Simulation

We developed a simulation environment to simulate various wayfinding scenarios. The simulation environment was written in Matlab programming language and run on an Intel Core i5 desktop computer. The simulation results were visualized as heat-maps over the sidewalk network of the University of Pittsburgh's main campus using Google Maps Javascript API.[4]

Sidewalk network database

We used the sidewalk network of the University of Pittsburgh's main campus for simulations. Kasemsuppakorn and Karimi (2008) constructed this sidewalk network through field survey. We also conducted another field survey for this work to find the number of landmarks and crosswalks in the campus sidewalk network. Segment attributes include slope, number of steps, length, number of crosswalks, sidewalk traffic, surface type, surface condition, width and number of landmarks. According to the ADA standards, step is a sudden elevation above 1.27 cm in sidewalk surface. A sidewalk network can be classified into three zones based on traffic amount: main zone, secondary zone and tertiary zone. Traffic amount may be identified by 1, 2 or 3 which means no traffic, light traffic and heavy traffic, respectively. The highest traffic occurs in the main zone and the lowest traffic in the tertiary zone. Kasemsuppakorn and Karimi (2008) reported, based on the field survey, that 71.4% of sidewalk surface types on the University of Pittsburgh's main campus are concrete and 23.8% are asphalt. The sidewalk network database contains 904 segments with a total length of 38.468 kilometers.

Simulation for wheelchair users

We simulated different wayfinding scenarios for wheelchair users by specifying different weights for the sidewalk parameters in Equation (2). All eight weights and all six values for each parameter were used in the simulation. This provided a total of 6^8 weights. For simulating a scenario in which a specific sidewalk parameter is a challenge for wheelchair users, higher weights are assigned to that parameter. For example, a weight of value 6 for the slope parameter indicates that the segment slope is a challenge for the user. In another example, a sidewalk segment is marked as impassable by considering its width to be less than 91.44 centimeters (according to the ADA standards) or including a step in that segment.

Simulation for individuals who are B/VI

For individuals who are B/VI, we simulated various wayfinding scenarios by specifying different weights for the sidewalk parameters in Equation (2). A total of 6^8 impedance scores for each segment were simulated. For simulation of wayfinding scenarios, we only considered those scores that are generated by specific parameters with certain weights. For example, to simulate a scenario in which a user wants to avoid crosswalks, we considered a high weight for the crosswalk parameter. Unlike simulations for wheelchair users, we did not impose any special restrictions on parameters for simulations for people with B/VI. As wheelchair users and individuals who are B/VI have different wayfinding needs, the simulation results are dissimilar for the two groups, indicating a different level of comfort, due to varying range of values, for each parameter.

Simulation results

Community heat-maps

As mentioned in the ‘Simulation for Wheelchair Users’ section, sidewalk segment impedance scores are classified into four categories: comfortable, semi-comfortable, uncomfortable and impassable. Segments with lower impedance scores fall into the comfortable category and those with higher scores into the uncomfortable category. Segments with steps or width of less than 91.44 centimeters are categorized as impassable for wheelchair users. Heat-maps showing comfortable segments in green, semi-comfortable in yellow, uncomfortable in red and impassable in black were generated. Such heat-maps, as a visualization tool, assist in realizing sidewalk accessibility and usability; the result of each simulation was visualized through a heat-map. Figure 1 shows a heat-map for wheelchair users. A segment color is determined based on the average of its weights in all 6^8 possible preferences that a wheelchair user can assign to the parameters. As shown in Figure 1, in this sidewalk network, some segments are marked as impassable (in black) due to the existence of steps or unfit width.

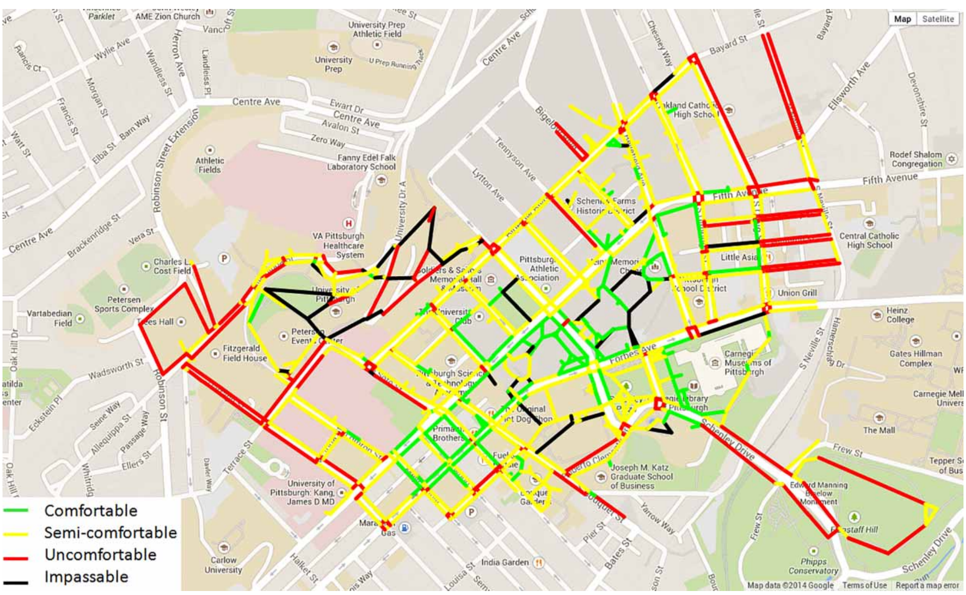

Figure 1. Heat-map for wheelchair users.

Applying the constraints for step and width parameters results in a different heat-map. These constraints may cause assignment of a segment to a different category for individuals who are B/VI. Considering the differences between the needs and preferences of wheelchair users and individuals who are B/VI, the heat-map for wheelchair users is different than the heat-map for individuals who are B/VI.

A community heat-map for individuals who are B/VI is shown in Figure 2. A segment color is determined based on the average of its weights in all 6^8 possible preferences that a user may assign to the parameters. In the heat-map, segments marked as comfortable are in green, semi-comfortable in yellow and those with higher impedance scores are in red.

A visual inspection of both community heat-maps reveals that comfortable segments for both communities (wheelchair users and individuals who are B/VI) are concentrated in the center of the University campus, whereas uncomfortable segments are mostly located in the outskirts of the network. Also, as it is visually clear, there are areas of the network with different colors in the two community heat-maps. Figure 3 shows the differences between the two community heat-maps. As seen in this figure, the community heat-map for individuals who are B/VI contains more comfortable segments than the one for wheelchair users. The same thing can be observed for semi-comfortable segments. The community heat-map for wheelchair users has more uncomfortable segments compared to the heat-map for the B/VI community. There is no impassable segment for individuals who are B/VI in this network. While the model and the parameter weight values are for experimentation, it is clear from these simulations that the proposed methodology can help assess the accessibility of the built environment visually, through heat-maps.

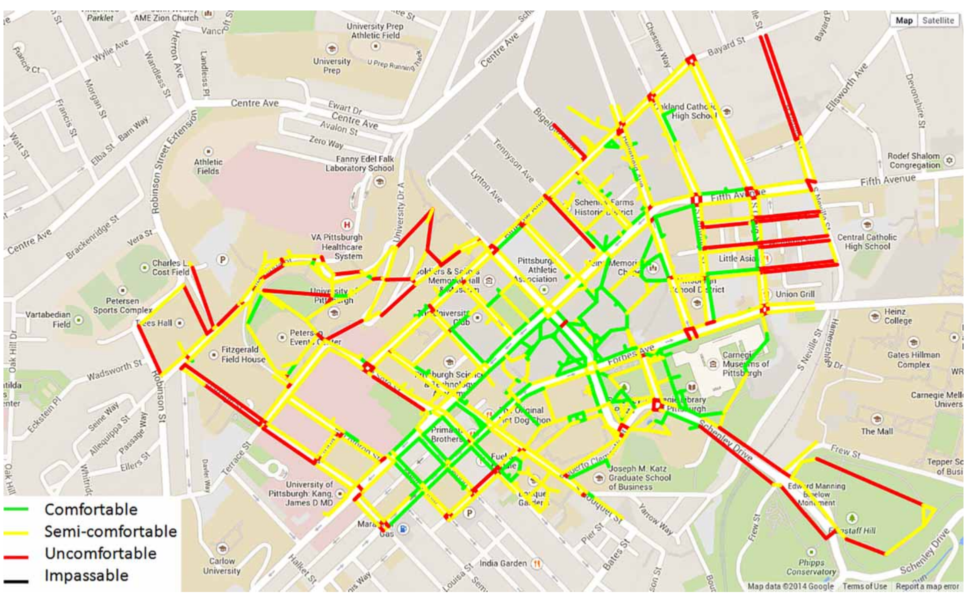

Figure 2. Heat-map for individuals who are B/VI.

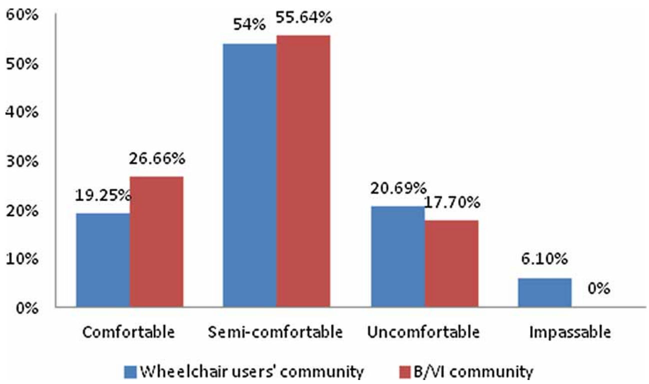

Figure 3. Differences between two community heat-maps.

Personalized heat-maps

We simulated two personalized scenarios for each user group. For each scenario, we assumed that only two parameters are important from the user's point of view. Note that the selection of appropriate parameters is not focused on in this work as the purpose of these simulations is demonstrating how the simulation methodology works and not validating the model or predicting user's behavior. In the first scenario for wheelchair users, users' preferences for slope and traffic were indicated with weights of 5 or 6, among the 6 possible values, otherwise they were assigned weights of 1 or 2. There are 2^8 possible weights for segments in this scenario. Figure 4 shows the heat-map based on the average of impedance scores. In the second scenario, users' preferences for sidewalk surface and width were indicated by weights 5 or 6, otherwise they were assigned weights of 1 or 2. Figure 5 shows the heat-map of the second scenario.

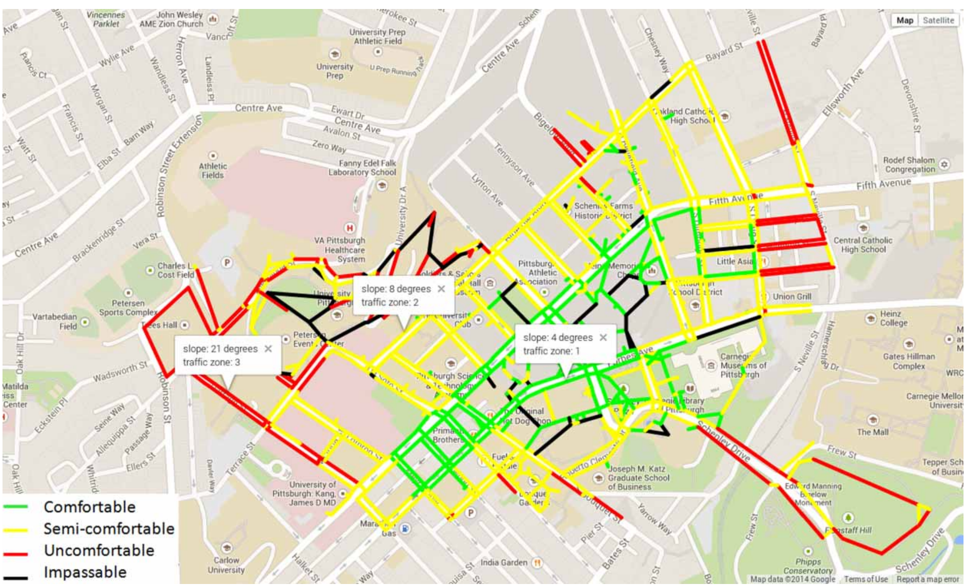

Figure 4. Heat-map for wheelchair users, first scenario.

Figure 6 shows the differences between the two personalized heat-maps for wheelchair users (Figures 4 and 5). As seen in Figure 6, the first scenario has fewer comfortable segments, more semi-comfortable segments and more uncomfortable segments than the second scenario for wheelchair users. Both scenarios have an equal number of impassible segments.

We also simulated two personalized scenarios for individuals who are B/VI. In the first scenario, users' preferences for slope and crosswalk were indicated with weights of 5 or 6, among the 6 possible values, otherwise they were assigned weights 1 or 2. There are 2^8 possible weights for segments in this scenario. The heat-map based on the average of impedance scores is shown in Figure 7. In the second scenario, users' preferences or length and traffic were indicated with weights 5 or 6, otherwise they were assigned weights of 1 or 2. The heat-map of the second scenario is shown in Figure 8.

Figure 9 shows the differences between the two personalized heat-maps for individuals who are B/VI (Figures 7 and 8). As seen in Figure 9, the first scenario has more comfortable segments, fewer semi-comfortable segments and more uncomfortable segments than the second scenario. Note that none of them has impassable segments.

Summary and future work

Accessibility of sidewalks for wayfinding of people with disabilities, in particular individuals who use wheelchairs and are B/VI, were simulated and visualized through heat-maps. This simulation and visualization approach can be used by urban planners to evaluate the accessibility of the built environment and find the accessibility gaps and by people with disabilities to find routes that are accessible to meet their needs and preferences, among others. In order to demonstrate how the proposed simulation methodology works and how the simulation results can be used, we employed a linear model and a

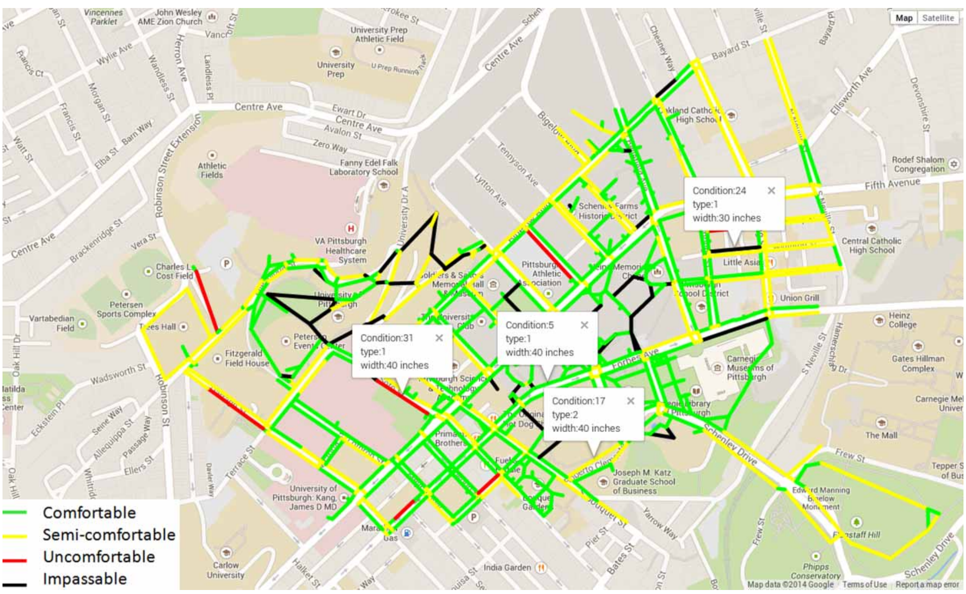

Figure 5. Heat-map for wheelchair users, second scenario.

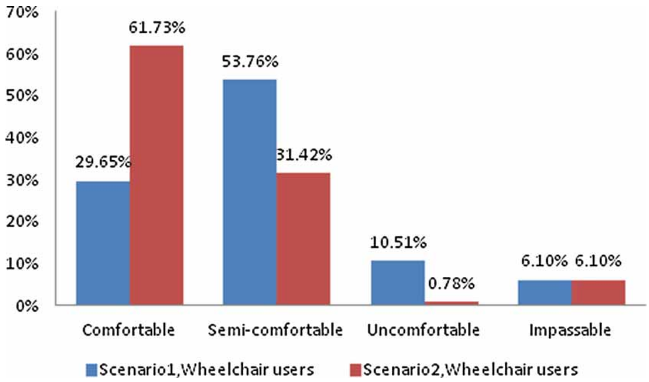

Figure 6. Differences between heat-maps in two scenarios for wheelchair users.

number of sidewalk segment characteristics as the model parameters. While any model that reflects human behaviors needs to be validated, primarily through subject testing, to assess its suitability, we did not validate this linear model since our main contribution in this work is to present a new methodology for evaluating the accessibility of sidewalks using any validated, existing or new, models.

A simulation tool based on the proposed methodology, to simulate and visualize the accessibility of the built environment, in particular sidewalk segments, needs to be built. This simulation tool will include a sensitivity analysis module and should be able to be integrated into existing and new software for planners and end users. For example, by integrating the tool with existing urban planning systems, urban planners can evaluate the accessibility of the built environment and find the accessibility gaps. An example application that benefits end users, in particular people with disabilities, is that they will be able to use the simulation tool, integrated with existing wayfinding

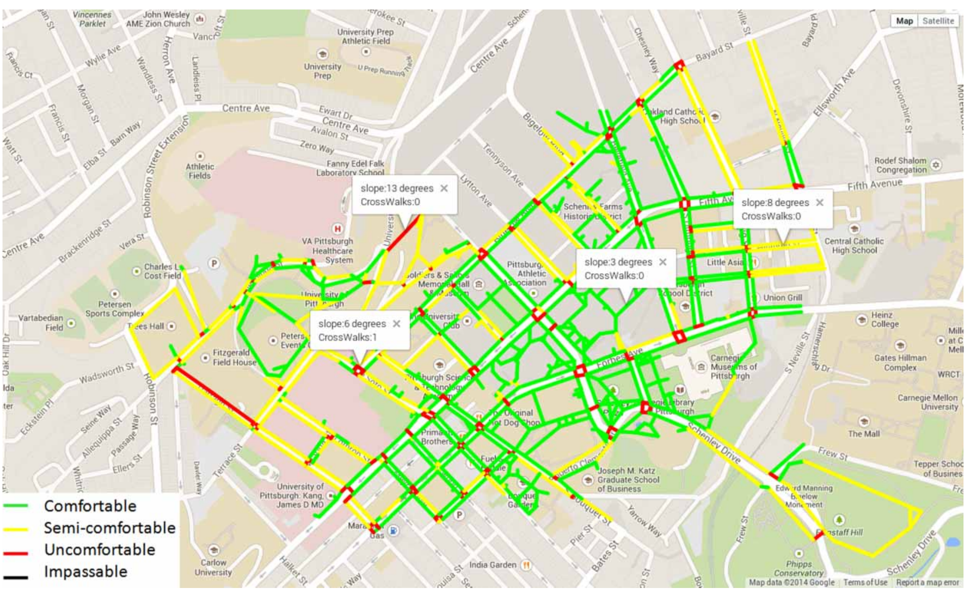

Figure 7. Heat-map for B/VI, first scenario.

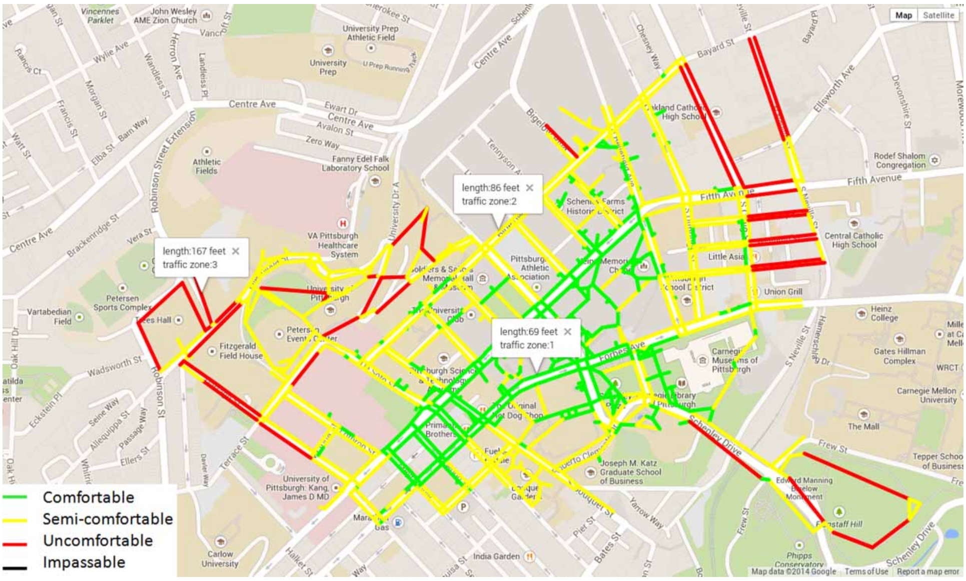

Figure 8. Heat-map for B/VI, second scenario.

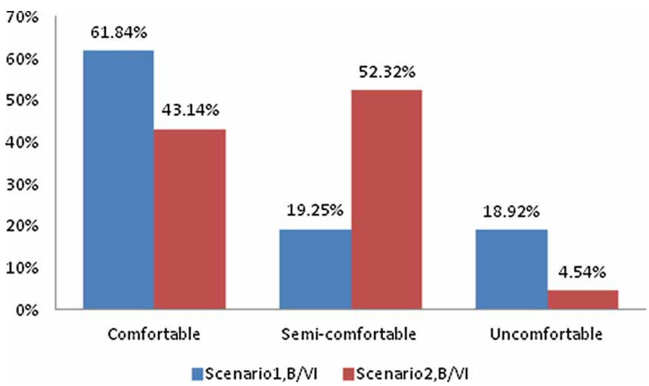

Figure 9. Differences between heat-maps in two scenarios for individuals who are B/VI.

and navigation systems and services, to visualize the accessibility of the traveling environment and find routes that are feasible, safe and comfortable for them. Examples of such routes are those shown in Figures 1, 2, 4, 5, 7, and 8 for the sidewalk network of the University of Pittsburgh's main campus.

Development of a simulation tool based on appropriate and tested models for people who are B/VI and use wheelchairs, at both community and individual levels, and development of a sensitivity analysis module for the tool are immediate future research directions.

Disclosure statement

No potential conflict of interest was reported by the authors.

Notes

1. http://www.humanware.ca.
2. http://www.senderogroup.com.
3. http://www.ada.gov/2010ADAstandards_index.htm.
4. https://developers.google.com/maps/documentation/javascript/tutorial.

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