Introducing the pedestrian accessibility tool: Walkability analysis for a geographic information system

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Introducing the Pedestrian Accessibility Tool
Walkability Analysis for a Geographic Information System

Alexander Erath, Michael A. B. van Eggermond, Sergio A. Ordóñez, and Kay W. Axhausen

The indexes for walkability proposed so far refer generally to the closest amenities and public transport stops and the existing network structure. The weights of the attributes do not reflect the independently measured preferences of the users and residents. Design attributes such as the location and type of crossings and walkway design features are usually surveyed in walkability audits. However, such attributes are usually not considered when pedestrian walksheds or other accessibility-based walkability indexes are calculated. Nevertheless, these design attributes are very relevant for actual planning decisions. The proposed walkability index can be behaviorally calibrated, has been implemented as a geographic information system tool, and is published as open source software. The pedestrian accessibility tool allows the evaluation of existing and future urban plans with regards to walkability. The tool calculates Hansen-based accessibility indicators with the use of a customizable specification of the generalized walking costs, and it incorporates user-defined weights of destination attractiveness. The basic user workflow of the tool is summarized. Three case studies show real-world applications of the tool to support the planning of pedestrian infrastructure in an urban context. With indications of potential areas of improvement that have been reported by pilot users working in an urban planning department, hints are also given for future research.

The potential of active travel modes, such as walking and cycling, to address both environmental and public health concerns, has resulted in a growing body of research across different fields. This research aims to capture how the built environment influences travel behavior. From various meta-analysis reviews, it can be concluded that the built environment directly influences walking (1–3). More specifically, the proximity to stores, a high intersection density, the job and housing mix, as well as the diversity of land use, influence walking positively (3), confirming that the propensity to walk is related to both infrastructure and destinations.

A shortcoming of previous studies is that they assess the influence of built environment variables from a macroscopic perspective. While the behavioral data of those studies usually stem from travel diary surveys, the variables that describe the built environment are typically available only in spatially aggregated form.

Based on a network survey of physical characteristics, location factors, and user factors of a pedestrian route, link, or crossing (4), pedestrian network audits allow for a spatially fine-grained, multicriteria assessment of walkability. Such assessment tools can include factorspecific weights recognizing that certain factors are more important to pedestrians than others (5).

Behavioral data collected with revealed and stated preference surveys allow one to quantify how pedestrians value different attributes describing the built environment. Eventually, these pedestrian preferences influence the walking experience and ultimately affect route and mode choice behavior.

In this paper, a software tool is presented that integrates the results from behavioral surveys with data collected in a network audit on a link level. This software tool has been developed in conjunction with Singapore’s Urban Redevelopment Authority (URA) as part of a larger project that aimed to quantify the walkability of Singapore’s city center.

The software tool computes a behaviorally founded walkshed and pedestrian accessibility index and combines the concept of accessibility with observed user preferences as identified in dedicated surveys. The disutility or impedance of a walking trip is thus not only quantified by the walking distance, but it also takes into account how well the built environment supports the pedestrians’ desire for a safe, comfortable, and pleasurable walking experience.

The remainder of this paper continues with a literature overview, followed by an outline of the requirements and functionality of the developed pedestrian accessibility tool (PAT). To highlight the use of the PAT, a detailed outline of the workflow is provided. Subsequently, to demonstrate the use of the PAT, several case studies are presented.

LITERATURE REVIEW

Level of Service

A range of methodologies are used in research and planning practice to assess how well a particular urban environment supports the needs of pedestrians. The most simplistic approach applies the concept of level of service (LOS) to pedestrian traffic. The LOS concept was originally developed to categorize the quality of traffic for highways based on the flow of traffic. Levels of quality, ranging from A (best)
to F (worst), are assigned to quality levels based on performance measures such as vehicle speed, number of car lanes, and pedestrian speed density; the pedestrian LOS is heavily dependent on auto volumes.

Network Audits

Appreciating that pedestrians also value pavement quality, lighting, and urban design characteristics, various researchers and planning bodies have conducted pedestrian network audits to collect such information on a link-by-link basis (6, 7). While in the past pedestrian network audits have primarily been conducted using a paper-and-pencil approach, mobile geographic information system (GIS) applications allow one to collect, digitize, and consolidate the collected data in a central database. The use of Google Street View, if available for the area of interest, seems also a meaningful option (8, 9), but it might have limitations such as traffic noise, facade transparency, or pedestrian footfall, should be included in the audit. Specialized software has been developed (10) to provide a comprehensive, quantitative assessment of the pedestrian environment and allow for objective comparisons of the LOS quality for pedestrians along different routes and generate suitable graphical output for public consultation and decision making.

Pedestrians’ Preferences

Revealed preference studies are a suitable research method to quantify pedestrian preferences and have been applied in various contexts. In a study conducted in Florida, it was identified that distance to school and the availability of a sidewalk significantly affect students’ willingness to walk to school (11). For shopping trips under a mile and access trips to rail stations, urban design qualities have the most pronounced impact (12). In Singapore, distance was to be the most significant factor influencing mode choice, but crossing a road is perceived as much as an additional distance of about 55 m. Similarly, climbing an overhead bridge was perceived as 90 m distance; crossing a car park adds another 36 m to the actual walking distance (13). In the city of Calgary, the importance of distance over other factors, such as the level of congestion, safety, or visual attractions, was identified (14). In San Diego and Minneapolis, a short distance had the strongest association with route choice; presence of a greenway and sidewalks and availability of destinations were positively associated with route choice as well (15).

In the city of Portland, Oregon, it was found that pedestrians were sensitive to attributes of the pedestrian network, intersection crossing aids, and elements of the street and block face environment along urban routes (6). Pedestrians were accepting detours to use more attractive facilities, although the tolerance with regard to the additional distance such detours involved was limited. In addition, it became clear how neighborhood-scale commercial streets serve both attractive destinations and walking routes.

A limited number of studies applied stated preferences techniques to describe pedestrians’ preferences. Climbing stairs and escalators was perceived as twice as negative as descending a flight of stairs and as 4.2 times more negative than in-vehicle travel time (16). The width of the sidewalk, separation from traffic, and availability of trees and greenery, as well as presence of other people to make a street more attractive for pedestrians, were found to be significant in image-based stated preference surveys (17).

Accessibility

Besides the quality of the pedestrian infrastructure to provide a safe, comfortable, and pleasurable environment (18), access to destinations in walkable distance is another important aspect of walkability. The concept of accessibility refers to the ability to reach desired goods, services, activities, and destinations. While measuring accessibility for motorized forms of transport is already well established in transport planning (19), only recently was the concept also adapted and applied to measure pedestrian accessibility (20, 21). WalkScore, a web-based service, assesses the walkability of a particular place by accounting how many amenities can be reached within walkable distance; in recent versions, network distances along road centerlines have been included (22).

Assessing Walkability

This research aims to integrate three strands of research to assess walkability: network auditing, pedestrians’ preferences, and accessibility. The LOS approach is certainly a useful assessment, but it does not account for comfort. By including aspects that account for how well a pedestrian facility is integrated into the urban design, the LOS approach can be extended to a multicriteria assessment to describe the walking comfort for pedestrians. However, since walking often is not a means to an end but usually a mode of transport to reach a destination to conduct a certain activity, the LOS approach lacks the important aspect of accessibility. Recent work that quantifies walkability by describing the amount and diversity of destinations that can be reached from a given location within walking distance neglects the preference of users in regard to design quality and different types of pedestrian infrastructure. At the same time, researchers have been able to quantify such preferences based on revealed and stated preference surveys, including mode and route choice experiments.

PEDESTRIAN ACCESSIBILITY TOOL

General Aim

The aim of the PAT is to compute the shortest perceived walking distances from one or several access points to all other access points that can be reached within a predefined walking time threshold. To obtain a perceived rather than an actual walking time, the PAT incorporates various factors contained in a pedestrian network that help to describe the quality of a walk, that is, the level of greenery along a link or whether stairs and crossings with traffic lights need to be traversed. Each link attribute should be weighted by a specific parameter. It is assumed that pedestrians perceive certain attributes dependent on the time they are exposed to it; for instance, greenery. Transversely, certain attributes are assumed to be independent of travel time. The presence of traffic lights or a flight of stairs are examples of such attributes. The travel time of one link is then defined as given by Equation 1:

$$t_p = t_{time} = \beta_{time} \left[ 1 + \sum \beta_X X_k \right] t_{act} + \sum \beta_X X_k$$

where

- \( t_{time} \) = time perceived along link \( i \),
- \( t_{act} \) = actual travel time of link \( i \),
- \( \beta_{time} \) = coefficient for travel time of link \( i \),
- \( \beta_X \) = parameter for attribute \( X \)
The pedestrian accessibility of one starting point is then defined according to Equation 2:

\[
A_i = \sum_j O_j e^{-\beta t_{i,j}}
\]

where

- \(A_i\) = accessibility of point \(i\);
- \(n\) = number of opportunities accessible from origin \(A_i\);
- \(O_j\) = opportunities at destination point \(j\);
- \(\beta\) = distance decay parameter, usually estimated to fit observed trip distance distribution; and
- \(t_{i,j}\) = time perceived walking between points \(i\) and \(j\).

The accessibility measure \(A_i\) can be interpreted as the perceived distance discounted sum of all destination opportunities.

Requirements

In several meetings with the URA’s Urban Planning Division, a series of requirements for the PAT were set. These requirements varied from the software platform to be used to the various performance indicators that should be calculated. The requirements are as follows:

- Software platform. Given the prevalence of the Environmental Systems Research Institute’s products within URA, the PAT should be developed as an ArcGIS add-in. In this way, existing and new file geodatabases could easily be used with the PAT.
- Input data:
  - The PAT should be able to read the pedestrian network from a shapefile or geodatabase as well as read link attributes stored in these data sources.
  - The PAT should be able to read the access points to the network from a shapefile or geodatabase as well as read point attributes stored in these data sources.
  - To support future analyses, the attribute names and the number of columns should be flexible and not hard coded.
- Computation:
  - The user should be able to define the distance decay parameter \(\beta\).
  - The user should be able to specify how the perceived walking duration \(d_{i,j}\) is calculated based on a series of link attributes and corresponding parameters.
  - To improve an iterative and interactive design process, planners should be able to make changes to the network, link attributes, and cost parameters and be able to perform an accessibility analysis within 30 s.
  - To make the analyst’s workflow more convenient, access points and the pedestrian network should be matched within the PAT and not by the analyst.
  - The output should include a cumulative opportunity index as well as a Hansen-based accessibility index with a custom distance decay parameter.
- Output:
  - The output should show the difference between perfect walkability and the walkable area according to the perceived walking costs.

\(\beta_t\) = travel time dependent coefficients,
\(\beta_n\) = travel time independent coefficients,
\(X_{ti}\) = set of attributes of link \(i\) related to \(\beta_t\), and
\(X_{ni}\) = set of attributes of link \(i\) related to \(\beta_n\).

The output should contain the traversable costs per link as well as the cumulative costs per link from the selected starting point, so that stored results can be visualized at a later stage.

Additional requirements. It is envisaged that a user wants to change network topology before using the PAT. To check whether the updated network topology is valid, the user should be able to use ArcMap’s shortest path algorithm.

Above all, urban planners were interested in a tool that was responsive enough to use in an interactive design session.

Each link in the pedestrian network possesses a series of attributes, such as width, cover, and number of steps, but also transparency and enclosure. In total, more than 30 attributes for a link were surveyed. The relative importance of each of the attributes can be derived from surveys, as was done for downtown Singapore, thus reflecting (average) pedestrian preferences, potentially by user group. While the requirements were set in a top-down fashion, the parameters measuring perceived walking time were intended to reflect the ultimate end user of the infrastructure: pedestrians. However, not all elements can be captured in either a network audit or a utility function. For instance, in regard to the quality of street music, vendors are hard to capture in a network audit, since they vary over time and place; and equating these elements to travel time gains is not appropriate and thus contributes to the limitations of the approach.

Implementation

The PAT was implemented as an ArcGIS add-in; the Environmental Systems Research Institute’s ArcGIS Desktop is considered to be the leading commercial GIS platform in the market (23). Add-ins can be written and developed in .NET or Java. Java was selected as the programming language because it is open source and platform independent. Figure 1 provides a schematic overview of the implementation of the pedestrian accessibility tool. Four layers combined provide the necessary input data for the PAT; they are shown in the left-hand side of the flow chart and below:

- Network layer. This is a special type of layer that relates junctions (graph nodes) and roads (graph links) stored in other layers. The network analyst extension of ArcMap provides a tool to generate a network representation from a simple line or polyline layer.
- Walkways layer. Walkways layers contain the geometrical information of the pedestrian network as well as the link attributes.
- Junction layer. This layer stores geometry and other information of nodes.
- Entries layer. The PAT requires a point layer representing walkable entries to destinations.

Several intermediate data structures are created by the PAT:

- Cost parameters. This is a cost map that contains the mapping between link attributes and the perception of the link costs.
- Weighted graph. Using the three-layer network representation and the cost function defined by the cost map, a weighted graph object is created in Java, which is optimized for graph algorithms.
- Walkways to paths. This map saves information of each walkway in the region of interest and works as a bridge between the walkways layer (input from ArcMap) and the paths layer (output to ArcMap) in the Java program.
- Walkways to points. This map relates each location included in the entries layer with a walkway.
Running the PAT results in three output layers. They are shown on the right-hand side of the flowchart presented in Figure 1.

**Workflow**

The graphical user interface guiding the PAT user through the scenario definition and computation process is shown in Figure 2. The front end of the PAT consists of four buttons in the ArcMap application. These four buttons are named Prepare, Parameters, Calculation, and Batch calc. They are ordered from left to right to represent the user workflow.

**Prepare**

As shown in Figure 2, in the first step (1a), the user sets a scenario name and defines which network layer and corresponding network data set, as well as the entries layer should be used for the analysis. In the second step (1b), the user is asked to select which columns are to be considered to define the pedestrian experience (cost function). In the third and final step (1c), the user selects which column (attribute) should be considered to represent the weight of an individual access point. The PAT will then generate a Java network object and relate the access points to the two nodes of the nearest (perpendicular) link.

**Parameters**

By clicking the button Parameters, the user is prompted to specify parameters for all network attributes that were previously selected to be relevant for the scenario (Figure 2, Window 2).

The window consists of two parts. The upper part contains settings of relevance for the analysis:

- Maximum distance is the distance from a single point that will be considered for single and multipoint analyses.
- Walking speed is the average speed of pedestrians.
- The parameter $\beta_{time}$ represents the value of time and is used for the time-dependent variables in the lower part of the Parameters window.
- The lambda parameter represents the distance decay factor.
- Weather condition describes the weather condition under which the assumed weather conditions in the scenario will take place.

The bottom part of the Parameters window shows the additional parameters specified in a separate text file. For each parameter, the beta value is stated, whether the parameter is time dependent and whether the parameter is different under different weather conditions (sunny, cloudy, rainy).

When Apply is pressed, the link costs will be updated: Each link in the network will have the perceived time to traverse a link assigned. This perceived time will be used in the routing algorithm.
Calculation and Batch Calculation

Once the analyst has selected a starting point for analysis and starts calculation, the PAT will prepare a subgraph and perform a one-to-n shortest path computation using the Bellman–Ford algorithm. For an analysis using a 500-m radius as a starting point, the calculation process should take about 20 to 40 s.

Output

After the calculation is completed, a pop-up Results window (Window 3) appears that shows key performance indicators. In addition, several layers are added to the ArcMap document.

The following link statistics are included in the output:

- Number of accessible links.
- Total accessible distance (sum of link length).
- Total perceived time (sum of the perceived time it takes to traverse each link).
- Accessible area. Area of the convex hull around the accessible access points.
- Perceived distance ratio. Total perceived distance spent on the links divided by the total link length. In this case, the perceived distance ratio is larger than 1, indicating that the perceived length is longer than the actual link length.
- Links walkshed ratio. Area reached divided over the entire area circle buffer from the starting point.

The following statistics for reached entries are included: (a) the number of accessible entrances; (b) the total accessible size: the number of accessible entrances multiplied by their respective weight; and (c) the total weighted size: the number of accessible entrances, where the weight of each entrance is discounted according to the perceived walking time to reach it according to the distance decay function and its parameter lambda.

Additionally, three layers are created:

- A layer with paths, including the minutes perceived walking time to reach this link from the selected starting point and the perceived walking time to traverse each link;
- A layer with entries with the perceived time it took to reach each entry; and
- A layer with the perceived walkshed (polygon) and the maximum distance (circle buffer).

Updating Results

If the network topology and attributes are not changed, the analyst can simply update the parameters and run subsequent analyses with varying start locations, distances thresholds, and cost parameters.

Usage

The suggested workflow for an analysis consists of two parts. First, as with any analysis, it is recommended to conduct a site visit; walking, after all, is a sensory experience, where infrastructure only forms one piece of the puzzle. The PAT is intended to support planning, and not to replace bottom-up planning with field observations of the pedestrian experience. A typical case study could...
involve the improvement of the pedestrian experience of a certain area, or the improvement of the pedestrian experience between two points, for instance, a train station and an office area. Traversing several routes in the study area will provide an indication of the pedestrian experience. Second, taking the results of the field visit as a basis, the PAT can be used to evaluate the effect of design interventions, such as the addition of cover or the introduction of grade crossings.

**CASE STUDIES**

In this section, three case studies are presented to showcase how the PAT can be applied to (a) illustrate how perceived and actual distance differ due to the respective pedestrian network attributes, (b) quantify the impact of adding new pedestrian infrastructure with regard to the accessibility of one particular location, and (c) quantify the impact of improving several locations simultaneously.

**Pedestrian Network Data**

An extensive pedestrian network covering the whole central planning area of Singapore provides a series of relevant variables describing the characteristics of the walkway and immediate built environment and serves as a basis for the presented case studies. The pedestrian network covers an area of about 4.7 km² and contains almost 420 km of walkways and 3,200 individual links. Figure 3 depicts the extent and detail of this pedestrian network. The network was audited in 2015 in the context of the aforementioned project in conjunction with URA. In addition, a data set featuring the location of more than 4,700 building entrance points and related building information is used for analysis with the PAT.

**Behavioral Parameters**

Behavioral parameters have been estimated based on a dedicated survey that integrated stated and revealed preference data of pedestrian route choice behavior and was conducted in Singapore (24). The utility function that describes generalized walking time given by Equation 3 has been identified based on the combined results of revealed and stated preference surveys that have been conducted as part of the same research project. It also combines a series of variables that have been identified to significantly influence the perception of walking time. Model parameters were estimated based on stated preference data; in the design of the experimental design, it was assumed that several attributes are contingent on time or weather, while others are independent of time or weather. This model specification was chosen after several pretests were performed. The corresponding parameter values are indicated in Table 1.

\[
 tp = \beta_0 \cdot \text{time} \cdot \left( \frac{1 + \beta_{\text{min}} \cdot \text{minor} + \beta_{\text{maj}} \cdot \text{major} + \beta_{\text{nb}}}{\text{throughblock}} \right) 
\]

\[
 \cdot \left( \frac{1 + \beta_{\text{u}} \cdot \text{sunlight} + \beta_{\text{r}} \cdot \text{rainy}}{1 + \beta_{\text{k}} \cdot \text{greenery}} \right) 
\]

\[
 \cdot \left( 1 + \beta_{\text{co}} \cdot \text{shops} + \beta_{\text{ct}} \cdot \text{stairs} + \beta_{\text{es}} \cdot \text{escalator} + \beta_{\text{fl}} \cdot \text{trafficlight} + \beta_{\text{cz}} \cdot \text{zebra crossing} \right) \tag{3}
\]

Depending on whether the individual variables are modeled as summand or interaction terms, the respective parameters have to be interpreted by direct comparison with the walking time parameter or as a factor that describes how much a certain attribute increases or lowers the relative perceptions of walking time.
TABLE 1  Default Parameters for Case Study

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Walkway Characteristics</th>
<th>Default Value</th>
<th>Interaction Term</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\beta_1)</td>
<td>na</td>
<td>-0.019</td>
<td>na</td>
<td>Walking time (min)</td>
</tr>
<tr>
<td>(\beta_{maj})</td>
<td>Along major road</td>
<td>0.593</td>
<td>Yes</td>
<td>Walkway through park as reference category</td>
</tr>
<tr>
<td>(\beta_{min})</td>
<td>Along minor road</td>
<td>0.473</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>(\beta_{tb})</td>
<td>Leads through a building</td>
<td>-0.169</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>(\beta_{cr})</td>
<td>Dummy for sunny weather conditions</td>
<td>1.5</td>
<td>Yes</td>
<td>Cloudy weather as reference</td>
</tr>
<tr>
<td>(\beta_{cs})</td>
<td>Dummy for rainy weather conditions</td>
<td>3.1</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>(\beta_{r})</td>
<td>With relevant greenery</td>
<td>-0.228</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>(\beta_{a})</td>
<td>With active frontage</td>
<td>-0.175</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>(\beta_{e})</td>
<td>Covered walkway</td>
<td>-0.175</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>(\beta_{w})</td>
<td>Dummy for sunny weather conditions</td>
<td>1.8</td>
<td>Yes</td>
<td>Cloudy weather as reference</td>
</tr>
<tr>
<td>(\beta_{w})</td>
<td>Dummy for rainy weather conditions</td>
<td>3.1</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>(\beta_{s})</td>
<td>Stairs</td>
<td>-0.04</td>
<td>No</td>
<td>Equals 2 min walking time</td>
</tr>
<tr>
<td>(\beta_{c})</td>
<td>Escalator</td>
<td>-0.02</td>
<td>No</td>
<td>Equals about 1 min walking time</td>
</tr>
<tr>
<td>(\beta_{t})</td>
<td>Traffic light</td>
<td>-0.02</td>
<td>No</td>
<td>Average waiting time corresponds to 1 min walking time</td>
</tr>
<tr>
<td>(\beta_{z})</td>
<td>Zebra crossing</td>
<td>-0.01</td>
<td>No</td>
<td>Correspones to about 30 s walking time</td>
</tr>
<tr>
<td>(\lambda)</td>
<td>na</td>
<td>330</td>
<td>na</td>
<td>Parameter to define distance decay function, refers to cloudy condition with average walking distance being 330 m</td>
</tr>
<tr>
<td>(r)</td>
<td>na</td>
<td>500</td>
<td>na</td>
<td>Considered radius for computing pedestrian walkshed</td>
</tr>
</tbody>
</table>

NOTE: na = not applicable.

The flexible architecture of the PAT also allows that both the number of attributes considered, the level of the corresponding parameters, and whether they are time or weather dependent can also be altered according to the user’s need. In this way, it is very easy to expand the functions that describe generalized walking time with new aspects, such as the width of the walkway, or to specify a scenario that better represents the behavior of elderly people.

Case Study 1. Representation of Perceived Compared with Actual Walking Distance

A rather simple but very helpful output of the PAT is the indication of a consolidated factor that describes the perceived as compared with the actual walking distance for each link in the network. Figure 4 depicts a map section covering Singapore’s central business district around Raffles Place. Links representing traffic light–controlled crossings feature the highest values of perceived distance, given that one assumes a penalty of an equivalent of about 1 min of walking time to account for the average waiting time at traffic lights. Furthermore, it is observed that the extensive underground, air-conditioned walkway network with partially active frontages yields relatively low perceived distance values for sunny weather conditions when compared with the reference category of a walkway that leads through a park. Because back lanes are often characterized by blind walls and come without any greenery or cover to protect from the tropical sun, this setting results in walking distances that are perceived as substantially longer than they actually are.

Case Study 2. Replacing Pedestrian Overhead Bridge with At-Grade Crossing

In this section, use of the PAT is highlighted by means of a case study near South Bridge Road, located in the center of Singapore. The number of at-grade crossings alongside South Bridge Road is limited. For instance, along the 240-m stretch (or 3-min walk) between Pickering Street and Cross Street, no grade crossings are present. Alongside this stretch are two pedestrian areas. Located on the east side of South Bridge Road is Nankin Road and Pickering Street, two carefully designed pedestrianized areas with a variety of restaurants and cafes. Located on the west side is a pedestrianized area with, among others, Hong Lim Complex and Chinatown Point. These two areas are connected midblock by a pedestrian overhead bridge. The situation is depicted in Figure 5. The current situation was taken as the baseline; as a starting point for this analysis, the staircase has been used. The what-if scenario involves the introduction of a level crossing at the location of the overhead bridge. The pedestrian network surrounding the area was carefully evaluated before the analysis was conducted.

Figure 6 shows results of the execution of the PAT. The circle depicts the beeline distance of 400 m. The polygon describes the outer hull of the accessible area by foot alongside the pedestrian network (equalling 400 m, but expressed in perceived distance) and the perceived walking time along these links. The upper graph shows that the overhead bridge restricts movement to the east side of the pedestrian overhead bridge. Since crossing the bridge is perceived as 4 min, traversing the remainder of the area on the east quickly amounts to a perceived walking time of 7 min (or a perceived distance of 400 m). To the west side, it can be seen that pedestrians can reach much farther; toward the west, the public housing estate with covered walkways and no major roads reduces the perceived travel time; the first major road (North Bridge Road) serves as a barrier.

The lower graph in Figure 6 highlights the hypothetical scenario when a grade crossing is introduced at the location of the overhead bridge. By introduction of this crossing, the pedestrianized areas toward the east along Nankin Road and Pickering Road are easily accessed within a perceived walking time between 2 and 4 min, a reduction of 3 min. A larger area can be reached within 7 min of walking. This is reflected by 38% more area and 47% more entrances than can be accessed in the what-if scenario.

Case Study 3. Assessing Impact of Pedestrian Infrastructure for Multiple Points of Interest

The batch calculation feature of the PAT allows the user to compute Hansen-based accessibility measures for a selected set of points of...
interest through a single command. To showcase this feature, the researchers expanded the pedestrian network at three intersections in Singapore’s central business district that currently feature only three crossing opportunities by adding a fourth pedestrian crossing, as shown in Figure 7, indicated by black lines.

In a first step, the Hansen-based accessibility measure for each point of interest was calculated (in this case, referred to as building entrances) in the map section for the baseline network. As defined in Table 1, a radius of 500 m was used as the distance threshold and the standard distance decay function for cloudy weather conditions. Gross floor area data that are available for each building were used to describe the attractiveness of destinations.

Subsequently, the same measure was computed, but based on the adapted pedestrian network that features the three additional crossing opportunities that were all modeled as traffic light–controlled crossings. For each point of interest, calculation was then done on the absolute and relative change in accessibility that those network improvements yield. As expected, the accessibility of buildings that are located close to the new crossing opportunities benefit most. The relative accessibility gains of more than 50% compared with the baseline scenario indicate the effectiveness of the proposed intervention. However, given the rather steep distance decay function (calibrated

---

**TABLE 1**

<table>
<thead>
<tr>
<th>Perceived Distance as Compared with Park, Sunny</th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt;0.25 min</td>
</tr>
<tr>
<td>---</td>
</tr>
<tr>
<td>Perceived Distance as Compared with Park, Sunny</td>
</tr>
<tr>
<td>0.25 min</td>
</tr>
<tr>
<td>200 m</td>
</tr>
</tbody>
</table>

**FIGURE 4** Perceived walking distances relative to walking through a park.

**FIGURE 5** Pedestrian overhead bridge connecting Nankin Road and Hong Lim Complex.
FIGURE 6 Pedestrian walkshed in baseline scenario with (a) pedestrian bridge and (b) at-grade crossing.
based on the observed average walking distance of about 270 m), the spatial extent of the impact is limited to the immediate surroundings of the crossing. Nevertheless, it can be seen that the impact of these crossings is not limited to the links adjacent to the crossings, but that benefits extend throughout a larger area.

**CONCLUSIONS**

The PAT allows planners to evaluate the perceived distance and travel time to surrounding destinations from a given starting point. Therefore, it is suitable to evaluate how improvements in pedestrian network connectivity and urban design variables both enhance the walkability of an area, with the basic unit of analysis being an individual building.

The PAT is intended to be used as a strategic planning tool, but it is not necessarily the ideal tool to quantify upgrade works, since they are typical after minor construction in a particular road. A typical case study could involve improvement of the pedestrian experience of a certain area, or improvement of the pedestrian network connectivity between two major pedestrian demand generators, for instance, a train station and an office area.

The methodology and software implementation was done in such a way that it can be directly transferred to assess any urban area for which a pedestrian network and the location of building (entrances) are available in a GIS data format. The cost parameters used as an input for the PAT have been estimated for Singapore’s downtown area and cannot directly be transferred to other settings. Distance decay parameters can be estimated from travel survey data, however; infrastructure-related parameters can be derived with quantitative reasoning. For instance, the penalty for signalized intersections can be set to be half the cycle time plus an additional penalty for waiting; a penalty to sidewalks of lower quality or with a higher exposure to traffic can be assigned. Subsequently, a sensitivity analysis can be performed on the chosen parameters, and the outcome on perceived walking time can be evaluated. In the same manner, parameters can be added to the utility function if behavioral data are lacking.

While the rather extensive design of the network audit was clearly tailored for research purposes, for practical applications, it is recommended to restrict the range of key attributes that are relevant for the given area and application. For the case of Singapore, those attributes should at least include link type, availability of a cover, width of the walkway, separation of traffic, facade transparency, and availability of greenery, as well as the type of vertical links and crossings. Limiting walkability to these attributes poses a risk of not identifying other elements that might be of relevance in the site being analyzed. Therefore, it is advocated that top-down desktop analysis go hand in hand with bottom-up fieldwork. For example, the field survey conducted in Singapore has shown that walkability is not limited to elements that can be measured in a pedestrian network. Pedestrians rated walks consistently higher where they noticed people socializing and noticed something interesting.

Expanding the scope of surveyed attributes would allow enhancing the scope of applications to be conducted with the PAT. For
example, a consistent audit of the number of steps required to traverse a link or cross a road would allow one to run analyses for people with special needs and to specify, for example, wheelchair accessibility.

The PAT has been developed as an add-in to ArcGIS. In several workshops with Singapore’s URA, in which the methodology and tool were explained, the need for a simpler, web-based tool has been voiced that also can be used for stakeholder communication. Key audiences of such a tool featuring a simplified interface and restricted functionalities are identified as urban and transport planning decision makers and local stakeholders, but also the general public, for example, through data journalism.

Published as open data, pedestrian network data could be used by developers to create applications that would help pedestrians find optimal routes according to personalized preferences and, for example, identify routes that optimally balance between exposure to rain and detour distance.

While the PAT can help planners to evaluate the impact of infrastructure measures on pedestrian accessibility, its functionality is not ideally suited to identify where network improvements convey the best potential and make most pedestrians benefit from it. To this end, the recommendation is to develop a pedestrian demand model that allows one to predict pedestrian link flows based on data that describe for each building or destination how many pedestrian trips it generates and attracts. Findings from the tracking survey and revealed preference experiment could then be used to calibrate such a model with regard to the walking distance distribution and pedestrian route choice. Implemented as another ArcGIS add-in, it would ideally complement the functionality of the PAT to prioritize and assess pedestrian infrastructure improvements.

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REFERENCES


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