







A Network Analysis Model to Measure the Walkability of Public Spaces

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Abstract. The ongoing shift from auto-oriented urban planning policies has led to a growing interest in the creation and management of public spaces in cities. Public spaces can act as an attraction for a city and have been proven useful for urban revitalization. However, it is not uncommon for many of those spaces to stay underutilized. The aim of this paper is to create a walkability utility index for every road segment that, when correlated with the population density of each area, is used to define the overall accessibility of public space on foot. This culminates into a set of novel equipotential mapping samples applied to a set of urban segments of Greek cities. The results of this paper lead to a different way of evaluating existing city plans, offer a useful tool to authorities in implementing urban regeneration works aimed at improving citizen well-being and, a keyway of evaluating new public space development projects.

Keywords: Accessibility · Walkability · Public spaces · Urban planning · Resilience

1 Introduction

Nowadays, more than 50% of the global population is concentrated in urban areas [1–4] and it is estimated that in the next 30 years, it will exceed 65% [4]. Following this phenomenon, many transport challenges have arisen, such as traffic congestion and greenhouse gas emissions [5–7]. For this reason, many international organisations (e.g., the UN, EU) have drawn attention to those problems and created a common agenda for 2030. More precisely, the UN [8] states at goal 11.2 that “*by 2030, provide access to safe, affordable, accessible, and sustainable transport systems for all...*”. Thus, urban planning is shifting from auto-oriented strategies to more sustainable solutions [6, 9, 10], such as walking [5].

The concept of walkability has emerged from various subjects, such as health, transport, and urban planning, over the years [11]. Walking is often preferred as a substitute for any means of transportation for short trips, and usually, it is combined with other means of transport, especially public transport. Additionally, it is almost impossible to complete any trip that does not include walking [10, 12] since it is the most inexpensive mean for everyone [13]. Also, walking has been linked to climate change [7]. Therefore

it is considered a core element of the sustainable cities [9, 14], as it is a well-known sustainable conveyance [5] and many governmental policies globally are promoting and encouraging walking since it has many health, environmental and social benefits [5–7, 10, 15].

Although many studies and theories have been developed around walkability from different perspectives, only a few researchers have linked walkability with public open spaces (POS). Hence, walkability is a current research topic with a research gap regarding walking access to open spaces. Moreover, the EU promotes sustainable modes of transport, like walking and cycling, and particular areas of the cities may require more drastic measures than others to adapt to that. For all those reasons, the primary aim of this paper is to correlate the population density of each area to define the overall walkability of public spaces through a walkability utility index for every road segment. Moreover, the paper's research questions are 1) the indication of which areas of the cities are less walkable, and 2) which POS are more walkable and what population density they cover.

2 Literature Review

The concept of accessibility has been examined over the decades, mainly through the prism of transportation planning, urban planning, geography, and policymaking [16–18]. Given its importance to various research fields and its extensive use, too many conceptual approaches in the literature make the notion quite vague and incohesive [19]. For instance, the term “accessibility” is often a substitute term for “mobility” and vice versa, with no particular effort at distinguishing between them [20]. According to Gould [21], accessibility is an essential notion through which development is measured, however, it is inadequate. Also, he describes the notion as “*slippery*” [28] because everyone uses that term until they face the difficulty of defining it and eventually attempt to measure it. Besides, the word “accessibility” signifies the proximity between two points [22], although addressing this idea of accessibility seems easy, it is quite difficult and challenging to implement it in practice [20]. However, accessibility usually refers “to the effort, means, or modes with which a destination can be reached” [24] and provides the necessary context between the associations of land uses and mobility.

Thus, the measures of accessibility vary but can be categorised into three groups. The first one is location-based (or zonal-level) [18, 23] accessibility measures that can be used from the viewpoint of the origin or the destination [23] and define the space dispersal of activities [18]. For example, the location of a business may express the potential number of its customers. That measure is mainly used by urban planners in Europe and is subdivided into cumulative opportunity measures, and potential accessibility measures [23]. Another measure that examines the economic viewpoint of accessibility is the utility-based measures. The centre of those measures is to analyse the benefits people gain from their level of access to specific land uses or activities [18, 23], and the most famous measure is that of log sum, which descends from the multinomial logit model [23]. Finally, the person-based measures explore accessibility at an individual level [23] that study how accessible activities are for someone to join within a particular time [18]. For instance, the specific number of activities that a person can attend at a particular time [23].

As it has already been stated, the notion of accessibility is quite vague [19], and it has been examined mainly through the prism of vehicles (e.g., public transport, cars) since, for many years, automobile-oriented policies had been applied. Nevertheless, more urban-friendly and environmentally-friendly alternatives have emerged, leading to the theory of “walkable cities”. According to that theory, cities are designed accordingly to enhance pedestrian movements [9], such as walking and cycling, which are core elements of sustainable cities [9, 14]. Similarly to accessibility, there are many definitions for walkability in the literature, especially in urban planning. In the urban agenda, walking is generally described as a “short distance moving from one point to the other” [5]. Another approach to walkability defines it as “*the extent to which the built environment is friendly to the presence of people walking, living, shopping, visiting, enjoying or spending time in the area*” [5]. Depending on the statement before, the proposed definition of walkability in the literature has been all the “*characteristics of the built environment and land use that may or may not be conducive to residents in the area walking for either leisure, exercise or recreation, to access services or to travel to work*” [14, 24, 25]. In general, the notion of making walkable communities is that people should become more active, in terms of walking, in the urban environment that lives in [25] but also create “*diverse, resilient, sustainable, friendlier and greener*” environments with healthier and happier people [26].

This research aims to provide a method to evaluate the walkability of POS and as extend the road network inside an urban area. Therefore, Patras’ POS will be examined using a utility measure consisting of four components: population density, road network (road type), pavement width and greenness along the road. That measure will highlight the service walking area in addition to the most walkable POS of Patras.

3 Methodology

3.1 Study Area

Patras is the biggest city in Peloponnese and the third biggest city in Greece. The population of the urban area of Patras was more than 167,000 people in 2011, according to ELSTAT. The study was conducted in the city centre of Patras and the areas around it, which covers 3.89 km² and houses approximately 50,000 residents. Patras was selected as an example of the methodology due to its high variance of combinations for the values of coefficients used, combining many different conditions in a small area and having enough POS distributed inside the urban fabric.

3.2 Data Collection and Preprocessing

Three components have been considered to measure the walkability of the POS of the city centre of Patras. Knapskog [27] have listed almost every attribute that affects walkability and has been examined in the literature (see Appendix). He summed up all the relevant attributes to the content of walkability and grouped them into three categories infrastructure and traffic, urbanity, and surroundings and activities. However, only three of them will be used in this paper as they can easily be obtained and applied to other

study areas as well. Therefore, the main hypothesis of the methodology is that three key factors are increasing the usage of active means of transport and thus influencing walkability to POS. Those factors are road type, pavement width, and greenness. The methodological process conducted in Python and QGIS was articulated in three stages: data collection and preparation, model selection and model calibration.

Initially, for the data collection, the locations of the most important POS were manually collected into a vector layer as points using satellite images. Next, the road network geometries were extracted using the OpenStreetMap (OSM) API [28]. The road network from OSM is already classified based on the road types, so only the information regarding the pavement width was added to the network, which was allocated manually with the help of high-quality satellite imagery and walking autopsies around the area of study. Lastly, the component of greenness was extracted from a satellite image that was downloaded. At the same time, the population density data that was retrieved from ELSTAT is required to estimate the number of people that access on foot every POS (Fig. 1).

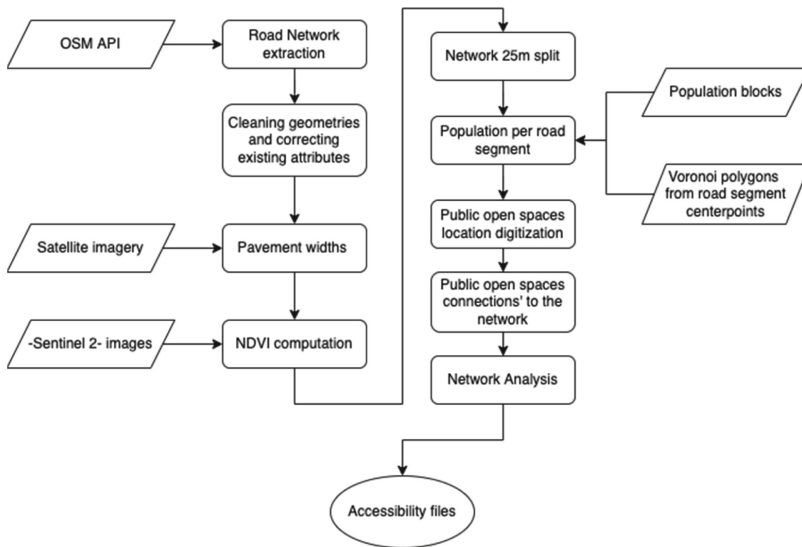


Fig. 1. Flow chart of the data needed and the pre-processing steps to calculate the walkability index

Next, all data were manipulated to calculate the walkability index. First, the POS were connected to the road network as, previously, public spaces were saved as a point vector layer. Thus, those points were connected to selected parts of the network manually and assigned a weight of 0 for the network analysis algorithm. When conducting the network analysis for an open public space, the connectors of that space are added to the graph and removed right after, to avoid being used in the analysis of other spaces since they are only virtual connectors and not an actual part of the network. Afterwards, the road network was cleaned using the GRASS GIS cleaning function to remove pseudo-nodes and cut the network at all the intersections so it can correctly be converted into a

graph. Then, Normalised Difference Vegetation Index (NDVI) which is the most applied method used to calculate greenness was computed as a metric of attractiveness for the road network. The data that was used was from Sentinel-2B for the tile T34SEH and the data take sensing time was on 29/3/2022. Sentinel-2 was chosen for this calculation because its products are in higher resolution (10m–20m–60m) and can compute more accurate results regarding greenness along the road. The computation for greenness was conducted according to the following function [29, 30].

$$NDVI = \frac{NIR - RED}{NIR + RED} = \frac{8 - 4}{8 + 4} \quad (1)$$

The values of this index range from -1 to 1 , and positive values represent greens, whereas negative values represent clouds, water, and snow. In contrast, values close to 0 represent empty areas, rocks, and bare soil. Essentially, NDVI calculates the given state of the plants' health based on how the plant reflects the light at the frequency of NIR and red. Afterwards, the NDVI raster image was clipped according to a 15m buffer along with the road network. Finally, after all that, the network was split with a maximum distance set to 25 m to increase the fidelity of the vector output. The roads were further separated at their middle point so the middle node could be used as a representative node for each road segment.

To calculate the number of people with good walking access to POS, the population density had to be further divided on every block side. Considering a constant population density amongst the area of each population block, the density factor of each block can then be multiplied by the area of the block attributed to each point to calculate the population of the point. It is noted that a point can receive populations from multiple population blocks, which are summed together to calculate the final population of that point. Equation (2) represents how population density was assigned to each side of the blocks.

$$A_i = \sum_{j=0}^n U_{ij} * P_j \quad (2)$$

where:

A_i is the amount of people to which node i is accessible.

P_j is the population connecting to node j .

3.3 Methods

The basic idea for the utility model derives from the negative exponential curve as a measure of utility. The model was chosen after the visualisation of real-world data for recreational walking showed great similarity to the form of the equation. According to the model, the further a person travels, the more their perceived discomfort increases, and the utility of the transport decreases. Thus, this discomfort increases depending on the distance the person travels and the conditions of the path the person travels along. The model does not consider the attractiveness of the destinations (i.e., POS) since its goal is not to predict the number of people a POS attracts but rather to use the road

network characteristics to locate parts of the study area that lack access to open public spaces as well as to evaluate how many people it is accessible based on a comfort or discomfort approach.

For the evaluation of the spots that are least accessible to open spaces, a network analysis was executed using the NetworkX Python library [37] to create the graph for the analysis. The network analysis is conducted using the NetworkX Dijkstra [31] implemented algorithm, with the weight of each segment calculated using the following equation.

$$V_{ij} = l_{ij} * (grn + pvm + rcl) \quad (3)$$

where

V_{ij} is the discomfort a person feels if they were to travel from node i to node j .

l_{ij} is the shortest distance thought the network from node i to node j .

grn is the greenness factor from node i to node j .

pvm is the pavement factor from node i to node j .

rcl is the road type factor from node i to node j .

The utility index from a node i to node a is equal to the negative exponential of the sum of the edge weights leading to the node a :

$$U_{ia} = e^{-\frac{1}{\mu} * \sum_{j=i+1}^{j=a} V_{ij}} \quad (4)$$

where:

U_{ia} is the utility of travel from node i to node a .

μ is a constant which needs calibration from real data depending on the mode of transfer.

A cut-off of a total weight equal to 3500 is passed into the Dijkstra function to reduce the computational time. For higher values of discomfort, the utility practically equals 0 and has no impact on the output. Therefore, the number of individuals to which public space is accessible by active means can be calculated by the sum of the product of each node's utility to that space with the population connected to that node for their transports (Eq. 3). The network nodes are used to create Voronoi polygons to cut the population blocks and distribute the area of the blocks to the nodes around them.

3.4 Model Calibration

The data used for this model were not collected particularly for this study, from residents of Patras, due to the COVID-19 pandemic. Instead, the selected model was fitted based on real-world data from the 2017 National Household Travel Survey (NHTS) that was conducted by the Federal Highway Administration of the U.S. Department of Transportation [32]. The method takes inspiration from the similar fitting performed by Yang with the 2009 NHTS data [33]. This study uses the day trip database from which the entries that refer to walking for recreation are extracted.

After removing the outliers (distances greater than 10 km and trips greater more than 3 h) 16.639 available trips were used as an input for the fitting. The utility function was fitted based on the cumulative frequency of the walking trip distance. Thus, the fitting metric used was the least-squares function and the final fitting value for the constant of the utility equation was computed equal to 917.97 with an R^2 value of 0.99 (Fig. 2).

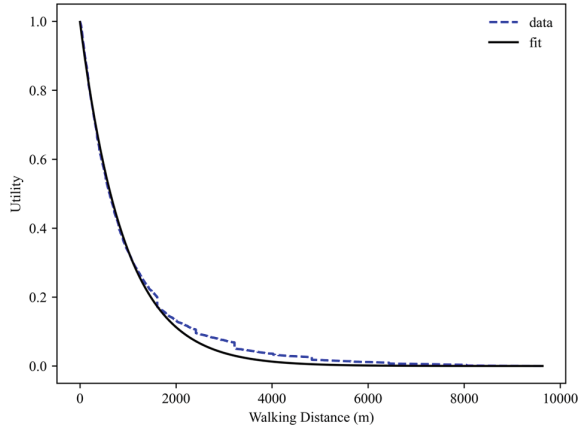


Fig. 2. The fitted utility function and the real distance decay curve

With the visualization of the predicted values over the real data, it is evident that the selected model produces a very accurate estimation of the utility of walkability. The closeness of the two curves indicates that the negative exponential function's selection best describes the walkers' behaviour.

There are a lot of previous studies that attempt to comprehend the factors that affect walking. According to Knapskog [27], infrastructure and traffic, urbanity, surroundings, and activities influence walking either positively or negatively. Infrastructure and traffic refer to the safety of pavements for pedestrians, while urbanity indicates the level of efficiency and how pleasant it is to walk, whereas surroundings and activities specify other attributes like the category and the variety of destinations or activities in a specific area. Keeping that in mind, the methodology focuses on the walkers' perception of comfort/discomfort based on the characteristics of the path they travel along. Although there is insufficient data to accurately quantify the value of the factors used by the discomfort equation for walking, in this study, three of the main attributes were suggested by Knapskog [27]: greenness, pavement width and the road type. Those factors were selected to measure attractiveness, safety, and comfort. However, there are no specific references in the literature to what extent those factors influence walking. Therefore, due to the lack of available data, to quantify those coefficients, the following assumptions need to be made:

- Every coefficient is independent.
- The discomfort function can be shifted, by the coefficients, a maximum of $\pm 30\%$
- The coefficient values follow linear equations.

- Pavement width and road type affect all three main factors (attractiveness, safety, and comfort), thus, we assume that they have a larger impact ($\pm 20\%$) on the discomfort equation than greenness ($\pm 10\%$) which only affects attractiveness and comfort.

For the needs of this paper, the following equations are assumed for each coefficient:

$$grn_j = \min(\max(0.90, 0.90 + NDVI_j), 1.1) \quad (5)$$

where:

grn_j is the greenness coefficient of edge j .

$NDVI_j$ is the NDVI of edge j

$$pvm_j = \max(0.8 + 0.1 * width_j), 1.2 \quad (6)$$

where:

pvm_j is the pavement width coefficient of edge j .

$width_j$ is the width of the pavement of edge

$$rcl_j = \max(0.80 + type_j), 1.2 \quad (7)$$

where:

rcl_j is the road class coefficient of edge j .

$type_j$ is a number corresponding to the road type of edge j (0 for primary, 1 for secondary, 2 for tertiary, 3 for local street and 4 for pedestrian streets).

4 Results

Figures 3 and 4 summarize the computed results. The outcome was produced by conducting the network analysis of every POS combining the results and keeping the maximum utility value for every segment as a measurement of the utility index. To be more specific, Fig. 4 represents the methodology flow that led to the computation of the final walkability index. The process indicates the POS most accessible by walking to the nearby population. Overall, regarding the network analysis, the results reveal that the study area has a good (>0.6) spatial coverage of walkability to open public spaces. However, a few regions can be identified where the accessibility is rated as mediocre (0.4–0.6). The average accessibility on every spot of the road network is 0.72 (sufficiently good), with a first-quarter value of 0.62.

The southern part of the map close to the network's borders has the lowest accessibility values. This is mainly caused because the network analysis does not consider the continuous urban fabric of Patras, and the borders of the study area do not correlate with the city's borders.

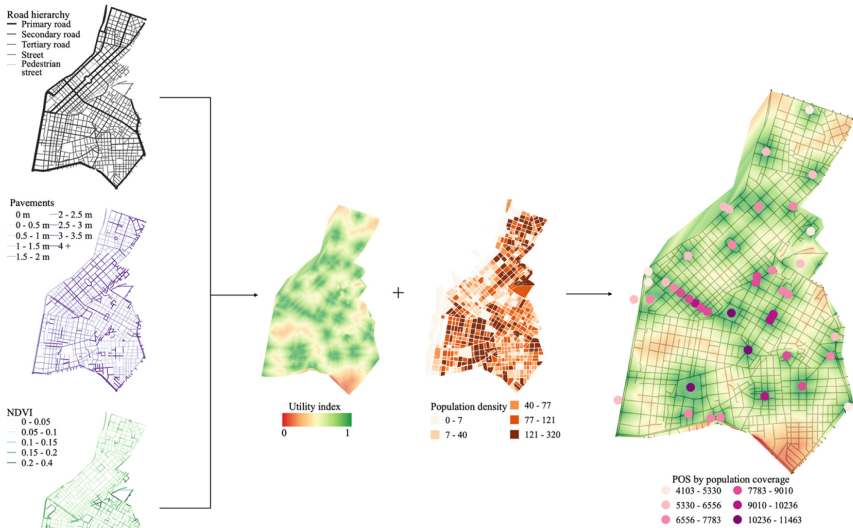


Fig. 3. Methodology flow to compute the accessibility index

Regarding the POS, Fig. 3 illustrates the number of people that can access the POS of the study area. Those facilities are categorised into six groups, and from that map, it is evident that only three spaces are accessible to more than 11000 people.

Finally, the most accessible POS in the study area base on population are shown in Fig. 4. Four out of five POS can be reached on foot by more than 10000 people each, while the fifth is accessible by more than 9800 people. Moreover, it was calculated that POS are accessible to around 71% of the population (35273 of 49761 people) by walking inside the study area. While the mean accessibility utility was estimated to be close to 73%. The population coverage is slightly less since the population density happens to be higher in regions with low accessibility.

5 Discussion

This paper aimed to develop a walkability utility index to examine how accessible are POS on foot and how many people can reach them. The methodology can be a valuable tool for evaluating the problematic areas and the spaces that affect the most people. Hence the method should also be suitable for planning and government practitioners as a macroscopic evaluation of infrastructure conditions. Also, this technique can also be used in measuring the accessibility of other places, for example, the walkability of schools and public buildings and identify the road segments that are prioritised for redevelopments. Another advantage of the methodology is that all the data used is accessible and very common, while the required software is open-sourced. Also, no other similar methods have developed in the literature that can be compared.

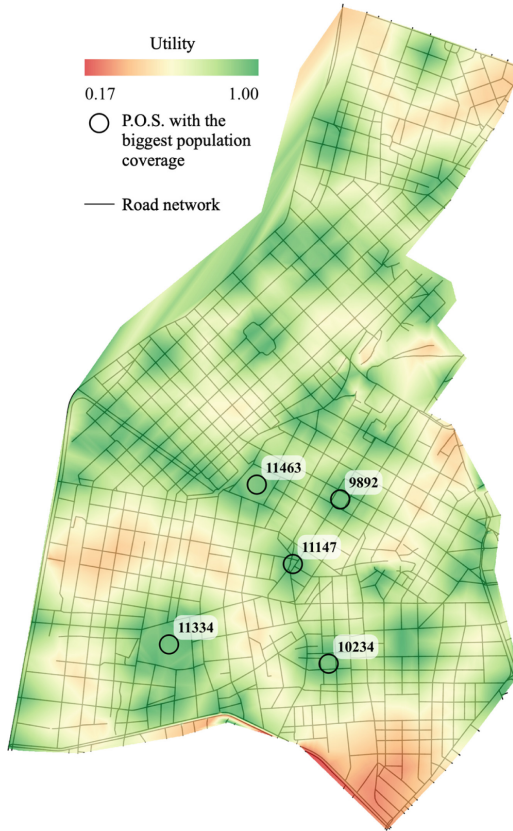


Fig. 4. Top five public open spaces with the biggest population coverage

Although the stated benefits of the developed methodology above, there are quite a few limitations that should be considered as suggested improvements for the future. This paper, due to the limitation of available data, only considers a straightforward metric to evaluate the attractiveness of each road segment. Thus, this method can only be used as a macroscopic evaluation of the conditions, and further analysis should be done where it is deemed necessary to conclude the possible actions for improvement of the infrastructure.

Furthermore, this paper only studies the accessibility from the prism of walkability. However, this method can also be applied to other modes of transport by manipulating the constant factor of the negative exponential curve to reflect the user behaviour of different modes of transportation. Also, the factors of the discomfort function may need to change depending on that mode's particularities. Lastly, it must be noted that the graph created for the network analysis of walkers is non-directional; however, when studying other means of transport, the analysis might need to be conducted on a directional graph.

It is worth mentioning that this research did not consider the slope of the road segments because of a lack of available data and because the studied area is mainly flat, however, in future work, a slope factor should be included in the equation. Another

suggestion for further research can be to modify the equation to combine the accessibility of public places into a new index that can be utilised to compare the accessibility of multiple urban areas.

Finally, the areas close to the network's borders have the lowest accessibility values. This is caused because the POS outside the study area cannot be included in the model because otherwise, they will affect the outcome of the utility score. A buffer around it should also be added and studied to get more accurate results in those areas. The outcome close to the border areas should be ignored in cases where the urban fabric continues beyond the border of the analysis. In cases where the urban fabric does stop at the border (like in the western border, where the urban fabric meets the sea), the values around it correctly represent the actual utility value.

6 Conclusion and Further Study

This paper has created a new walkability measure that ranks POS according to the road network. The suggested methodology examines every road segment that, when correlated with the population density of each area, is used to define the overall accessibility of public spaces on foot. Apart from the ranked POS according to the population cover, the methodology highlights the underutilised facilities, and the road network segments that need redevelopment. Our focus was to develop an easily applied index with accessible data and open-sourced software programs so it can be implemented in other cities. The suggested index is a useful measure to evaluate locations in general. Additionally, this method can be applied to other modes of transport by manipulating the constant factor of the negative exponential curve to reflect the user behaviour of different modes of transportation and the factors of the discomfort function depending on that mode's particularities.

Although the great potential of the index, some limitations may be considered for further study. Firstly, further studies must be conducted to justify the constant factor of the negative exponential curve to be accurate. Another aspect suggested for further research is adapting the index to more attributes for walkability. Lastly, after examining all the above, it would be beneficial to study whether the index can be reformed to examine the accessibility of locations by other modes, such as bicycles.

Appendix

See Table 1.

Table 1. Factors and attributes relevant for assessing walkability [27].

Factors	Attributes	Highly walkable	Walkable	Somewhat walkable	Not walkable	
		←-----→				
Infrastructure and traffic	Street or road character	Streets			Roads	
	Pedestrian infrastructure	Sidewalks			No sidewalks	
	Crossings	Defined crossings at same level			Barriers and detours for pedestrians	
	Traffic volumes	Low			High	
	Speed levels	Low			High	
	Pollution and noise	Low			High	
	Traffic safety	High			Low	
	Universal design	High accessibility			Low accessibility	
Public transport connectedness	Walking routes connected to public transport stops			Walking routes not connected to public transport stops		
<i>Descriptive conclusion</i>						
Urbanity	Density	High			Low	
	Proximity	Short distances			Long distances	
	Connectedness	Connected to the city structure			Its own structure	
	Scale	Pedestrian			Vehicle-oriented	
	Orientation of buildings	Buildings oriented along the street				Buildings receded from the street/road
		Building head-to-head to the sidewalk				Parking in front of buildings
	Block sizes	Small blocks			Long/large blocks	
	Permeability	High Permeability			Non-permeable	
	Pedestrian network	Coherent pedestrian network, short cuts			Infrastructure as barriers for pedestrians	
	Urban structure	Grid			Cul de sacs	
	Parking lots	Few			Many, making barriers	
	Urban spaces and parks	Many			Few/none	
Green	Street trees, parks etc			No greenery		
Street furniture	Many			Few		
<i>Descriptive conclusion</i>						
Surroundings and activities	Destinations	Multiple			Few or no one	
	Activities	Multiple			Few or no one	
	People walking or staying	Many			Few or no one	
	Facades	Active			Closed	
	Mix of functions	High			Low	
	Vibrancy	High			Low	
	Maintenance	High			Low	
	Experienced safety	Feels safe			Feels non-safe	
Wayfinding	Easy			Not easy		
<i>Descriptive conclusion</i>						

References

- Georgi, J.N., Dimitriou, D.: The contribution of urban green spaces to the improvement of environment in cities: Case study of Chania, Greece. In: Science Direct Elsevier (2009). <https://reader.elsevier.com/reader/sd/pii/S0360132309003564?token=B41D64AD5B6CC2BEAEF57DD779F81DAF9956A44EA10E9C7703BBA03705B7B85A70FA5AAE8522D9145001BC67067FF6A8&originRegion=eu-west-1&originCreation=20210925133336>. Accessed 25 Sep 2021

2. Gómez, F., Jabaloyes, J., Montero, L., De Vicente, V., Valcuende, M.: Green areas, the most significant indicator of the sustainability of cities: research on their utility for urban planning. *J. Urban Plann. Dev.* **137**, 311–328 (2011). [https://doi.org/10.1061/\(ASCE\)UP.1943-5444.0000060](https://doi.org/10.1061/(ASCE)UP.1943-5444.0000060)
3. Richardson, E.A., Mitchell, R., Hartig, T., de Vries, S., Astell-Burt, T., Frumkin, H.: Green cities and health: a question of scale? *J. Epidemiol. Community Health* **66**, 160–165 (2012). <https://doi.org/10.1136/jech.2011.137240>
4. Giuliani, G., et al.: Modelling accessibility to urban green areas using open earth observations data: a novel approach to support the urban SDG in four European cities. *Remote Sens.* **13**, 422 (2021). <https://doi.org/10.3390/rs13030422>
5. Rafiemanzelat, R., Emadi, M.I., Kamali, A.J.: City sustainability: the influence of walkability on built environments. *Transp. Res. Procedia* **24**, 97–104 (2017). <https://doi.org/10.1016/j.trpro.2017.05.074>
6. Liao, B., van den Berg, P.E.W., van Wesemael, P.J.V., Arentze, T.A.: Empirical analysis of walkability using data from the Netherlands. *Transp. Res. Part D: Transp. Environ.* **85**, 102390 (2020). <https://doi.org/10.1016/j.trd.2020.102390>
7. Frank, L.D., Appleyard, B.S., Ulmer, J.M., Chapman, J.E., Fox, E.H.: Comparing walkability methods: creation of street smart walk score and efficacy of a code-based 3D walkability index. *J. Transp. Health* **21**, 101005 (2021). <https://doi.org/10.1016/j.jth.2020.101005>
8. UN Transforming our world: the 2030 Agenda for Sustainable Development | Department of Economic and Social Affairs. <https://sdgs.un.org/2030agenda>. Accessed 6 Apr 2022
9. Turoń, K., Czech, P., Juzek, M.: The concept of a walkable city as an alternative form of urban mobility. *SJSUTST* **95**, 223–230 (2017). <https://doi.org/10.20858/sjsutst.2017.95.20>
10. D’Orso, G., Migliore, M.: A GIS-based method for evaluating the walkability of a pedestrian environment and prioritised investments. *J. Transp. Geogr.* **82**, 102555 (2020). <https://doi.org/10.1016/j.jtrangeo.2019.102555>
11. Majic, I., Pafka, E.: AwaP-IC—an open-source GIS tool for measuring walkable access. *Urban Sci.* **3**, 48 (2019). <https://doi.org/10.3390/urbansci3020048>
12. Koenig, J.G.: Indicators of urban accessibility: theory and application. *Transportation* **9**, 145–172 (1980). <https://doi.org/10.1007/BF00167128>
13. Walkable Communities. <https://www.walkable.org/>. Accessed 23 Mar 2021
14. Moura, F., Cambra, P., Gonçalves, A.B.: Measuring walkability for distinct pedestrian groups with a participatory assessment method: a case study in Lisbon. *Landsc. Urban Plan.* **157**, 282–296 (2017). <https://doi.org/10.1016/j.landurbplan.2016.07.002>
15. Zhang, X., Melbourne, S., Sarkar, C., Chiaradia, A., Webster, C.: Effects of green space on walking: does size, shape and density matter? *Urban Stud.* **57**, 3402–3420 (2020). <https://doi.org/10.1177/0042098020902739>
16. Yan, X.: Evaluating household residential preferences for walkability and accessibility across three U.S. regions. *Transp. Res. Part D: Transp. Environ.*, **80**, 102255 (2020). <https://doi.org/10.1016/j.trd.2020.102255>
17. Wachs, M., Kumagai, T.G.: Physical accessibility as a social indicator. *Socioecon. Plann. Sci.* **7**, 437–456 (1973). [https://doi.org/10.1016/0038-0121\(73\)90041-4](https://doi.org/10.1016/0038-0121(73)90041-4)
18. Anjomshooa, E., Lamit, H. B., Shafaghat, A., Khan, T.H.: Accessibility measurement techniques in urban studies: a comprehensive review. **16** (2017)
19. Pirie, G.H.: Measuring accessibility: a review and proposal. *Environ. Plan A* **11**, 299–312 (1979). <https://doi.org/10.1068/a110299>
20. Handy, S.: Is accessibility an idea whose time has finally come? *Transp. Res. Part D: Transp. Environ.*, **83** (2020). <https://doi.org/10.1016/j.trd.2020.102319>
21. Gould, P. R.: *Spatial Diffusion* (1969)
22. Ingram, D.R.: The concept of accessibility: a search for an operational form. *Reg. Stud.* **5**, 101–107 (1971). <https://doi.org/10.1080/09595237100185131>

23. Geurs, K. T.: Transport planning with accessibility indices in the Netherlands (2018)
24. Telega, A., Telega, I., Bieda, A.: Measuring walkability with GIS—methods overview and new approach proposal. *Sustainability* **13**, 1883 (2021). <https://doi.org/10.3390/su13041883>
25. Su, S., Pi, J., Xie, H., Cai, Z., Weng, M.: Community deprivation, walkability, and public health: Highlighting the social inequalities in land use planning for health promotion. *Land Use Policy* **67**, 315–326 (2017). <https://doi.org/10.1016/j.landusepol.2017.06.005>
26. (2020) What is Walkability? (And Why it Matters for Health, Resilience, Happiness). In: *Blue Zones*. <https://www.bluezones.com/2020/05/what-is-walkability-and-why-it-matters-for-health-resiliency-happiness-and-sustainability/>. Accessed 23 Mar 2021
27. Knapskog, M., Hagen, O.H., Tennøy, A., Rynning, M.K.: Exploring ways of measuring walkability. *Transp. Res. Procedia* **41**, 264–282 (2019). <https://doi.org/10.1016/j.trpro.2019.09.047>
28. OpenStreetMap contributors (2022) OpenStreetMap. In: *OpenStreetMap*. <https://www.openstreetmap.org/>. Accessed 12 Apr 2022
29. Abutaleb, K., Freddy Mudede, M., Nkongolo, N., Newete, S. W.: Estimating urban greenness index using remote sensing data: a case study of an affluent vs poor suburbs in the city of Johannesburg. *Egyptian J. Remote Sens. Space Sci.*, (2020) <https://doi.org/10.1016/j.ejrs.2020.07.002>
30. NDVI: Normalized Difference Vegetation Index For Agriculture. <https://eos.com/make-an-analysis/ndvi/>. Accessed 4 May 2021
31. Dijkstra, E.W.: A note on two problems in connexion with graphs. *Numer Math* **1**, 269–271 (1959). <https://doi.org/10.1007/BF01386390>
32. US Department of Transportation National Household Travel Survey. <https://nhts.ornl.gov/>. Accessed 15 Apr 2022
33. Yang, Y., Diez-Roux, A.V.: Walking distance by trip purpose and population subgroups. *Am. J. Prev. Med.* **43**, 11–19 (2012). <https://doi.org/10.1016/j.amepre.2012.03.015>