User-Centric Pedestrian Navigation: Transfer Study from Sofia to Tokyo

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Abstract

Pedestrian route-finding applications are commonly used for urban navigation. These applications typically focus on finding the shortest or fastest route and rarely consider pedestrian safety or comfort. Such non-utilitarian factors can be accounted for by incorporating a walkability index in the routing algorithm. This study transfers an existing user-centric pedestrian routing approach from Sofia to the Tokyo wards of Shinjuku and Bunkyo. The approach considers the heterogenous needs of different user groups by using an adjustable weighting scheme. Data from OpenStreetMap and local open datasets on streetscape features such as sidewalk width and incline are standardised and walkability scores are calculated using the developed framework.

Results indicate that the Sofia routing approach is cleanly transferable to Tokyo. Wasserstein's, Cliff's delta, and Kolmogorov-Smirnov's statistical tests show that calculated walkability scores remain consistent with the intentions of the framework. Calculated routes in Tokyo successfully increase average walkability compared to the shortest path, without excessively increasing length. Walkability scores are unevenly distributed in the study area, with street segments in pedestrianised residential areas with many parks receiving high scores, while major roads that lack dedicated pedestrian infrastructure receive lower scores. The different user profiles lead to spatially distinct walkability patterns. Scores for tourists are high around densely concentrated commercial facilities, while scores for wheelchair users are high along arterial roads with wide sidewalks and low incline. By successfully adapting an existing pedestrian routing method, this study demonstrates that using user-specific walkability scores for route-finding can be a viable approach in different contexts.

1. Introduction

Pedestrian route-finding applications are commonly used for urban navigation, particularly by individuals unfamiliar with a certain area. These applications typically focus on finding the shortest or fastest route and do not consider non-utilitarian factors such as safety and comfort (Siriaraya et al., 2020). This can exclude certain population groups, such as the elderly or wheelchair users, for whom the quality of the pedestrian environment is more important (Van Cauwenberg et al., 2012; Horn, 2024).

One possible means by which route quality can be accounted for in pedestrian routing algorithms is through the integration of a walkability index. Walkability refers to the extent to which an urban area supports walking (Saelens & Handy, 2008). Many existing indices consider macro-scale built-environment features that locate amenities within walking distance of residents, such as residential density and land-use mix (Venerandi et al., 2024). Micro-scale environmental factors that more directly affect the safety and comfort of walking, such as sidewalk width and pavement quality, are less common (Fonseca et al., 2022). Additionally, many existing walkability indices do not differentiate among the needs of different user groups, leading to inconsistencies between calculated walkability and individuals' walking experiences (Jehle et al., 2024).

Previous studies have consistently found a link between high walkability and increased rates of walking among urban residents (Hino et al., 2022; Lefebvre-Ropars et al., 2017). This is particularly relevant in Japan, which is facing the dual challenges of an ageing population and an increased duration of poor health associated with increased life expectancy (Tokudome et al., 2016). Encouraging physical activity through walking provides an effective strategy for reducing negative health outcomes, particularly among older adults. Over 40% of adults in Japan aged over 45 years are physically inactive (Annear et al., 2020), which puts them at greater risk of non-communicable diseases such as cancer and heart disease (Hayasaka et al., 2009). As many older adults experience mobility impairments, environmental factors such as slope and pavement quality have a greater effect on walkability than for the wider population (Hanson et al., 2012).

This study examines the spatial transferability, from Sofia to a case study area in Tokyo, of an existing user-centric pedestrian routing method. Driven by the availability of open data, Sofia has seen the development of multiple walkability indices in recent years (Petrova-Antonova et al., 2025). Sofia serves as a strong example due to its diverse urban form and mixed walkability conditions, making it a realistic and transferable testbed for developing walkability indices and pedestrian routing methods. The method transferred in this study incorporates detailed streetscape data, including sidewalk width and pavement type, to model pedestrian-friendly routes (Mitev et al., 2026).

The following research questions (RQ) are considered:

(RQ1) To what extent are walkability indices developed for Sofia applicable to Tokyo?

(RQ2) How effectively does the proposed walkability-based route-finding algorithm enhance walkability relative to the shortest path in Tokyo?

Through adapting an existing routing method, this study provides evidence on the relevant environmental factors for pleasant pedestrian routing in Sofia and Tokyo. This can facilitate the

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exchange of best practices in walkable urban design between the two cities.

The rest of the paper is organized as follows. Section 2 outlines the existing routing methodology and covers related work on walkability assessments in Tokyo and the transferability of walkability indices. Section 3 introduces the study area, describes the datasets, and outlines the data preparation and processing methodology. Section 4 reports the empirical results for both research questions. Section 5 concludes with a summary of results and directions for future work.

2. Previous & Related Work

2.1 User-Centric Pedestrian Routing

The existing routing method developed for Sofia finds pedestrian-friendly routes by including a micro-scale walkability index in the route-finding algorithm (Mitev et al., 2026). This index was primarily developed using a dataset containing the pedestrian network in Sofia Municipality as vector geometry. Streetscape indicators relating to sidewalk width, traffic perception, slope, point of interest (POI) accessibility, and segment type are considered. As will be described in further detail in Section 3.2, each segment in the pedestrian network is given a normalised score in the range [0-1] for each indicator.

The preferences of different population groups, such as children or the elderly, are accommodated by using different weights for each indicator. For example, the 'elderly' profile includes higher weights for slope and sidewalk width than the 'generic pedestrian' profile. Weights were mapped from previous walkability studies by using correspondence matrices, which allowed for existing weighting schemes to be re-used despite differences in the features considered (Appolloni et al., 2019; Ruiz-Padillo et al., 2018; Fonseca et al., 2022; Akinci et al., 2022; Ye, 2020; Zuo at al., 2021; Golan et al., 2019; Hassanshahi et al., 2023; Jehle et al., 2024). The final walkability score for a segment is calculated as a weighted sum of each indicator using the weights for a particular population group. As each set of weights sums to 1, the final walkability score for a segment is given on a 0-1 scale.

Pedestrian routes are calculated using Dijkstra's shortest path algorithm with a modified cost function, as defined by Taylor et al. (2026). A constant 'cost reduction factor' in the range [0-1] controls the effect of walkability scores on edge cost. The cost function is given below:

$$edge\_cost = edge\_length \times (1 - (walkability \times cost\_reduction\_factor)) \quad (1)$$

2.2 Walkability Assessment in Japan

Most existing work on walkability indices in Japan has focused on validating indices developed in the United States. The ANEWS walkability instrument has been shown to reliably predict physical activity in Japan (Inoue et al., 2009). However, questions on housing density and sidewalk characteristics had to be rewritten to fit the Japanese context. Walk Score has also been shown to be a reliable macro-scale indicator of neighbourhood walkability in Japan, offering a practical tool for assessing walkability without requiring detailed geographic data (Koohsari et al., 2018).

The Japanese Walkability Index (JWI) is a macro-scale walkability index that primarily measures accessibility to points of interest such as parks and supermarkets (Shimizu et al., 2020). Previous work has found that the JWI is more effective than Frank's Walkability Index (FWI) for predicting step counts among residents in Yokohama (Hino et al., 2022). As the JWI was designed specifically for use in Japan, while the FWI was designed in the USA, this indicates that consideration of local factors is important in designing an effective walkability index.

Analyses of the effects of micro-scale streetscape factors on pedestrian volumes in Tokyo have found that attractive streetscapes and a feeling of safety influence perceptions of walkability and are linked with higher pedestrian volumes (Capitanio, 2019; Gao et al., 2025). Despite this, few studies have focused on the development or application of micro-scale walkability indices in Japan (Annear et al., 2024). The Microscale Audit of Pedestrian Streetscapes (MAPS) has been shown to be effective for assessing micro-scale walkability in Japan (Saito et al., 2022) and has previously been used to analyse walkability for the elderly in Tokyo (Annear et al., 2024). However, this approach relies on trained auditors, which limits its use to smaller geographic areas.

2.3 Spatial Transferability of Walkability Indices

Many existing walkability indices have been developed for specific geographic contexts, taking local data availability into account during variable selection. This can improve the accuracy of calculated scores but makes replication in other contexts more difficult (Venerandi et al., 2024). Previous work by Lefebvre-Ropars et al. (2017), which transferred the Pedestrian Index of the Environment (PIE) from Portland, Oregon to the Greater Montreal Area, has shown that despite this, the spatial transfer of existing indices can be both feasible and worthwhile. PIE was chosen to be transferred due to its proven validity and methodological improvements over other indices. Although sidewalk density was omitted from calculations due to a lack of available data, high PIE was shown to be strongly correlated with residents choosing to walk for short trips in Montreal.

In Sofia, high localised differences in the quality of the pedestrian environment allow improvements in route quality to be achieved by a walkability-aware pedestrian routing method without requiring a significant increase in route length (Taylor et al., 2026). As Tokyo features similar differences between wide arterial roads and narrow residential streets, such methods are potentially transferable to this context. This is further motivated by similarities in the urban form of the two cities, such as the presence of fine-grained blocks, dense intersections, and narrow streets.

3. Methodology

This section describes the study area, data collection, preparation and preprocessing.

3.1 Study Area

The Tokyo study area includes the neighbouring wards of Shinjuku and Bunkyo, both located in the centre of the city (Figure 1). This area was selected to provide a diverse range of streetscape environments, featuring wide arterial roads as well as narrow residential streets without separated sidewalks. Western Shinjuku is characterised by dense commercial areas with fine-grained blocks and strong transit access, supporting higher walkability. The Nishi-Shinjuku neighbourhood in southwestern Shinjuku provides a markedly different pedestrian environment from the rest of the study area, featuring wide roads, separated

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pedestrian infrastructure and tall skyscrapers. Bunkyo and eastern Shinjuku are primarily residential areas, which are characterised by narrow streets and irregular block sizes. Neighbourhoods to the east of the study area also feature greater topographic variation than in the west, which influences pedestrian comfort through slope.

Figure 1. The 23 special wards of Tokyo with the study area highlighted and Nishi-Shinjuku marked in a light-yellow colour (Tokyo station is marked as a reference point).

3.2 Data Collection, Preparation and Preprocessing

To generate the results, a six-step data collection and preprocessing workflow is developed. First, the pedestrian and vehicle street networks, as well as supplementary sidewalk polygons, a DEM model, and a map of the POIs of the study area are collected. Then, the pedestrian network is enriched by extracting features from the supplementary data as described in the sections below. This results in a single, easily scorable network which can be evaluated and used for routing.

3.2.1 Pedestrian and Vehicle Networks: The base geometry for both wards is the OpenStreetMap street network, retrieved with the OSMnx library using Overpass API (OpenStreetMap, 2026; Boeing, 2025). For each ward, two graphs are downloaded and clipped to the boundaries of the ward: a walk network which provides the pedestrian edges to be analysed and scored, and a drive network used to attach attributes related to traffic. The graphs are downloaded with topological simplification enabled but are additionally configured to include pedestrian infrastructure tags and values of the attribute 'crosswalk' such as 'footway', 'crossing', 'tunnel', etc.

3.2.2 Pedestrian Network Edge Types: The Sofia model assigns each edge type of the pedestrian graph a score from a fixed, predetermined mapping (Mitev et al., 2026). To match the OSM edge types to the ones used in the Sofia study, the 'highway', 'footway', and 'service' fields are used and mapped to the most relevant Sofia edge type. When direct mapping is not possible, types are mapped to the most similar one.

3.2.3 Sidewalk Width: Sofia's study measured sidewalk width by using the city's cadastre data and applying Voronoi diagram-based estimation. For this study, similar data are derived using Project PLATEU, the Japanese Ministry of Land, Infrastructure, Transport and Tourism's (MLIT) 3D city model (MLIT, 2026). This dataset is inconsistent, and the areas of Shinjuku and Bunkyo feature a mix of streets with sidewalks and multi-use streets without sidewalks, so width is collected for only 9% of edges.

3.2.4 Slope: The Sofia model bins each segment's longitudinal gradient (≤ 2 % → 1.0, ≤ 5 % → 0.7, ≤ 8 % → 0.35, else 0.0). For Tokyo, the gradient is calculated using Geospatial Information Authority of Japan (GSI) DEM5A data with a resolution of 5 metres (Geospatial Information Authority of Japan, 2026). The data is fetched as PNG-encoded elevation tiles from the GSI XYZ service. Elevation is sampled at each edge's endpoints and additionally in the middle of an edge for edges longer than 50m. Slope data is collected for 93.3% of all edges, as edges of type 'bridge' and 'tunnel' don't follow the same incline as surrounding topography.

3.2.5 Adjacent Traffic: The traffic component requires per-edge adjacent lane count and speed limits. This is achieved by attaching each pedestrian edge to the best overlapping parallel 'drive' edge from the OSM data. When mapping the data, three explicit decisions are made: (i) car-free edges with no parallel roads are assigned the maximum score, (ii) mixed-use streets are assigned the score derived from their number of lanes and speed limits, (iii) when an associated road lacks a 'maxspeed' tag, a class-based Japanese urban default is used.

3.2.6 Points of Interest: The Sofia POI scoring counts accessible POIs according to the retail-use score of the Pedestrian Environmental Quality Index, developed following National Association of City Transportation Officials (NACTO) guidance (Batteate & Nasser, 2015). The Tokyo Analog uses Overture Maps places, queried per ward directly from the Overture public S3 bucket with DuckDB and then scores them according to the same methodology. Due to the high density of POIs in Tokyo and the fact that the Sofia network spanned the whole municipal area, Tokyo edges are mapped to more POIs on average.

4. Results

This section reports on the two research questions posed by the study. Section 4.1 addresses RQ1 - the extent to which the profile-based Sofia-based walkability indices, with their formulas and weights frozen, translate to the Tokyo wards of Shinjuku and Bunkyo. Section 4.2 addresses RQ2 – whether profile-based routing focused on walkability produces walking routes with higher average walkability than the shortest paths.

4.1 Transferability of the Walkability Indices (RQ1)

4.1.1 Edge Attribute Scores: The transferred attribute scores roughly reproduce the shape of the scores achieved for Sofia, with the below described patterns occurring in both wards and explained by the data (Table 1). To measure the difference in scores, both the means and Cliff's delta are used. Since Cliff's delta is a directional metric, it should be defined that the Tokyo data was used as the first argument and the Sofia data as the second. A positive score means that Tokyo's values are higher, and a negative score means that Sofia's values are.

Firstly, the scores for 'type' are generally lower than in Sofia because the Tokyo data includes many road lanes that are traversable by both vehicles and pedestrians. Secondly, the adjacent traffic scores are higher than in Sofia due to lower speed limits on one- and two-lane streets and the fact that the Tokyo wards have a higher concentration of pedestrian-only streets. Additionally, the Sofia data features more boulevards and a ring road. POI scores also run far higher than in Sofia, explained by the high urban density of the study area. The Tokyo data also has a much higher width score, but many fewer edges are scored for width as compared to Sofia.

Feature	Shinjuku mean	Bunkyo mean	Sofia mean	Cliff's δ
Type	0.41	0.47	0.55	−0.21
Width	0.95	0.86	0.33	+0.91
Slope	0.86	0.84	0.83	+0.08
Traffic	0.90	0.90	0.83	+0.34
POI	0.054	0.044	0.0075	+0.22

Table 1. Mean component scores and Cliff's δ as compared to Shinjuku.

4.1.2 Profile Distributions: When the components are combined under the six frozen profile indices, the Tokyo profile scores are close to those of Sofia. Mean general walkability is 0.540 for Shinjuku and 0.556 for Bunkyo against 0.514 for Sofia (Table 2). The relative ordering between user groups is kept the same in Tokyo as in Sofia. Wheelchair and Women profiles score highest, followed by the General, Elderly and Children scores. The tourist score is still the lowest. However, this can be attributed to the nature of POI mappings, as they are mapped only to the closest pedestrian edge, and a low POI score is not indicative of poor POI connectivity.

Additionally, every cell shows a positive δ and the displacements are uniformly small as the Wasserstein distance is upper-bounded by 0.071 (Table 2). This means that the Tokyo distributions are consistently shifted to the right of the Sofia distributions. Such results are consistent with the idea that Tokyo's data causes a coherent translation of the index.

Third, the divergence between Bunkyo and Sofia is consistently slightly larger than the divergence between Shinjuku and Sofia. This is indicated by the larger Cliff delta for all profiles and a larger Wasserstein distance and Kolmogorov-Smirnov statistics for five out of the six profiles. The statistics with the most meaningful differences are the KS D values, which indicate the largest gap between the score distributions of Sofia and the wards. This, together with the other statistics, shows that the Tokyo and Sofia score distributions are close, but the Tokyo scores are more concentrated in one part of the range. It can also be verified by the wheelchair score, which has the highest KS D, which can be justified by its heavy reliance on sidewalk width as a parameter.

Profile	Sofia	Shinjuku μ / W / KS *D* / δ	Bunkyo μ / W / KS *D* / δ
General	0.514	0.540 / 0.040 / 0.178 / +0.134	0.556 / 0.043 / 0.220 / +0.196
Elderly	0.500	0.533 / 0.039 / 0.199 / +0.147	0.546 / 0.046 / 0.225 / +0.201
Children	0.491	0.522 / 0.040 / 0.201 / +0.140	0.537 / 0.047 / 0.227 / +0.194
Women	0.534	0.559 / 0.035 / 0.165 / +0.115	0.574 / 0.041 / 0.211 / +0.178
Tourists	0.364	0.376 / 0.031 / 0.204 / +0.089	0.385 / 0.027 / 0.245 / +0.137
Wheelchair	0.521	0.568 / 0.059 / 0.279 / +0.174	0.590 / 0.071 / 0.290 / +0.234

Table 2. Mean scores per user profile, Wasserstein distance to Sofia, Kolmogorov-Smirnov statistics and Cliff's δ.

4.1.3 Spatial Patterns: The results show that walkability is unevenly distributed and structured in the study areas (Figs. 2, 3). Moreover, the structure of the profile scores matches across the two wards. The following spatial trends are observed:

First, a low-scoring corridor of boulevards defines both wards (Figs 2, 3). Major arterial streets lacking dedicated pedestrian infrastructure span Shinjuku and Bunkyo, forming continuous corridors of low scores which contrast with the higher scores of the residential areas between them. This is justified by differences in traffic and sidewalk conditions along these streets, as well as their actual types, which result in a lower score. This uniform distribution of low scores shows that the framework reliably distinguishes busy roads from adjacent local streets, even where they run side by side. This ability is the basis of the walkability-focused routing discussed in Section 4.2.

Secondly, high scores tend to concentrate in areas which are structurally opposite to the low-scoring ones (Figs. 2, 3). The best scores are in heavily pedestrianised residential areas, especially those with more parks. Specifically in Shinjuku, the well-connected area around the station and the western skyscraper grid of Nishi-Shinjuku have a high concentration of above-average scores.

The scores are distributed in spatially distinct patterns, consistent with what can be theorised from knowing the weights. The most extreme example of this is the tourist profile, which collapses to a high-scoring core around densely concentrated commercial facilities such as the central Bunkyo and the area surrounding the train station in Shinjuku. This is caused by the increased POI weights, which are the biggest difference between the tourist profile and other profiles. The wheelchair profile shows the opposite trends. The arteries with high sidewalk width and low incline become the most highly scored routes, and the inner-neighbourhood segments receive low scores. The fact that each user group's high and low scoring areas are distributed in a manner that is easily predictable by the weight vectors confirms that the user-group weighting produces actual walkability maps as it did in Sofia.

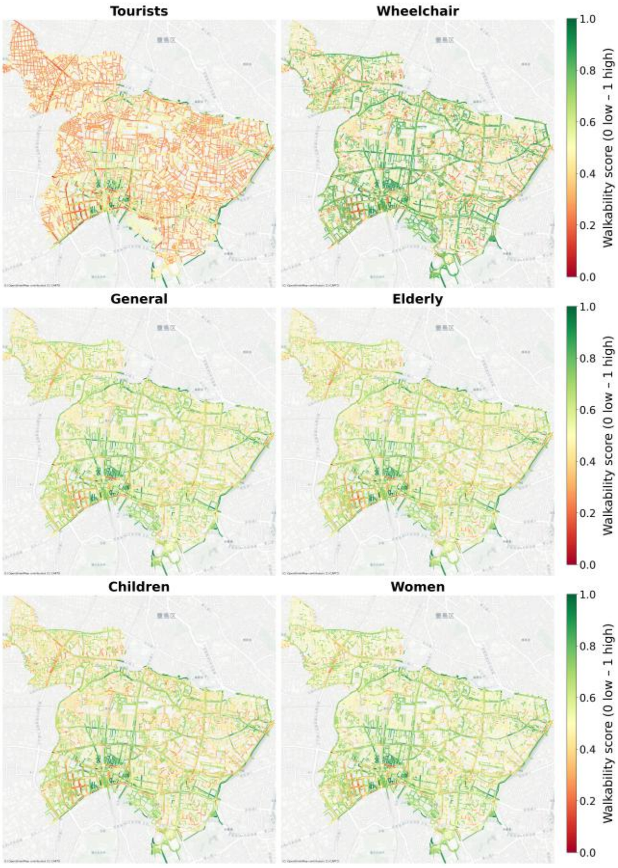

Figure 2. Shinjuku score maps. Basemap: © OpenStreetMap contributors © CARTO

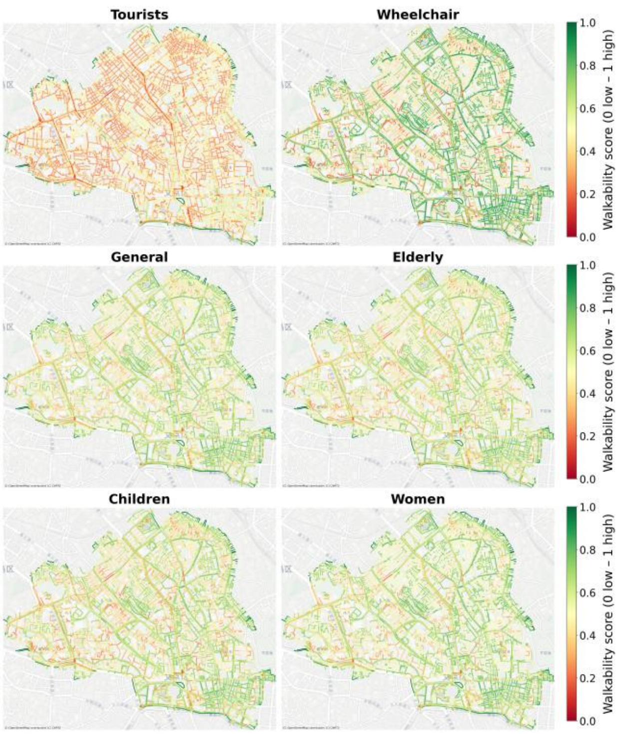

Figure 3. Bunkyo score maps. Basemap: © OpenStreetMap contributors © CARTO

4.2 Walkability-Based Routing (RQ2)

The walkability routing uses Dijkstra's algorithm with the frozen Sofia cost function, accepting the best-scoring path only where it is within 20% of the shortest-path length. Pathfinding is evaluated using two experiments. First, a large-N randomised experiment that establishes the full-scale gain of the framework (4.2.1) and a set of origin-destination pairs benchmarked against path recommendations from Google Maps.

4.2.1 Large Scale Experiment: First, a routing experiment was run with 300 random origin-destination pairs per ward. The pairs are sampled so that their shortest-path length is between 300 and 2000 metres to simulate credible walking distances. They are then evaluated across all six user profiles. The results (Table 3) show that the routing benefit is substantial and robust across categories. These results are best evaluated against the base means from Table 2. Here, a mean increase of 0.101 (for the Shinjuku General profile) represents a 20% increase relative to the ward's mean walkability. Moreover, these gains are much higher than the score deviations introduced by the cross-city frozen transfer.

Two structural patterns arise in the results. The gain is consistently larger in Shinjuku than in Bunkyo across all user groups, exposing a property of the Shinjuku pedestrian network. The area has denser grid-like streets, which offer more walkable options and generally produce more paths within 20% of the shortest possible one. On the other hand, Bunkyo's more constrained and less dense street network led to the highest-scoring paths being closer to the shortest one (Fig. 4, 5).

Second, five of the categories are bundled together in their relative gain, with the wheelchair profile clearly having a larger gain than the others. This is explained by its heavy dependency on slope and sidewalk width. The wheelchair group has both the largest mean gain and the lowest percentage of improved pairs for both wards, indicating that it can make improvements on paths where it can choose a better alternative street rather than making small deviations along its path.

Profile	Shinjuku Mean Gain (% of positive routes)	Bunkyo Mean Gain (% of positive routes)
General	+0.101 (94 %)	+0.068 (90 %)
Elderly	+0.097 (93 %)	+0.066 (90 %)
Children	+0.110 (93 %)	+0.074 (90 %)
Women	+0.097 (94 %)	+0.067 (91 %)
Tourists	+0.096 (92 %)	+0.058 (89 %)
Wheelchair	+0.151 (91 %)	+0.107 (89 %)

Table 3. Mean gain (difference between the route returned by the algorithm and the score of the shortest route) and percentage of A-B pairs for which the best route is not the shortest one.

4.2.2 Comparison to Google Maps: Running the Google Maps comparison on six origin-destination pairs verifies that the most walkable paths diverge from the Google recommendation by design. Where a more pleasant parallel street is available, the best path's overlap with the Google recommendation drops substantially (Fig. 4). This happens because the algorithm takes a short detour for a better-scored route that a distance-minimizing algorithm wouldn't select. A second test, running through Bunkyo (Fig. 5), shows two distinct routes. One of them closely follows Google Maps and is preferred by tourists because of its preference for busy streets and high POI concentration. The other, quieter and less car-centric path is chosen by all other groups.

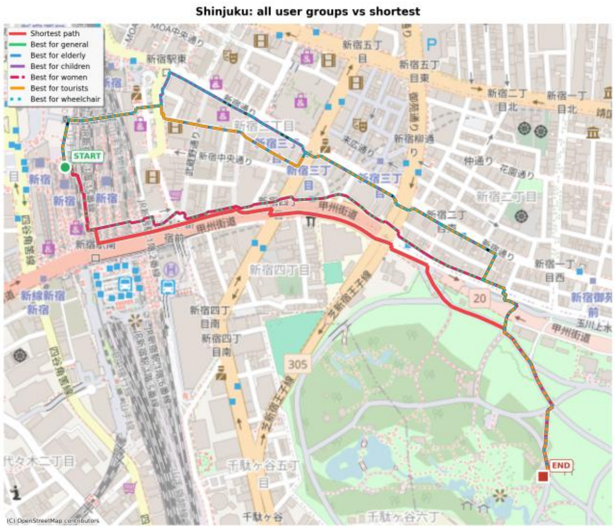

Figure 4. Route comparison in Shinjuku.

Figure 5. Route comparison in Bunkyo.

5. Conclusion and Future Work

This section consists of the main findings, limitations, and future directions.

5.1 Conclusion

The aim of this study is to transfer a user-centric pedestrian walkability index and its accompanying routing method, originally developed for the city of Sofia, to two urban wards in Tokyo, and to evaluate whether the transfer preserves the index's internal logic and routing performance. This is tested with the scoring formulas and user-group weight vectors frozen.

For RQ1, the frozen-formula transfer produced a fully scored network. Moreover, statistical tests on the distribution of feature scores and walkability scores, such as Wasserstein's, Cliff's delta and Kolmogorov-Smirnov's, revealed that the transferred scores remain consistent with the intentions of the framework. The minor shifts in walkability scores are attributable to differences in the data between the two cities.

For RQ2, a randomised experiment over 300 origin-destination routes showed that the walkability-based routing method improved average walkability compared to the shortest path on 89-94% of trips. When comparing routes against the shortest path and the Google Maps-recommended route, it was observed that different user profiles generate different routes, defensible by features of the pedestrian environment.

Taken together, these results indicate that a multi user-centric walkability index developed for the city of Sofia is cleanly transferable to the city of Tokyo. The index preserves its internal logic and practical routing benefits.

5.2 Limitations and Future Work

A limitation of this study is that sidewalk width data from Project PLATEAU is only available for approximately 9% of network edges (Section 3.2.3), which constrained the scores of the width attribute, which is especially important for the wheelchair user group.

Future work should focus on validating the walkability index against actual pedestrian path data. This would be the way to confirm if the proposed paths reflect user behaviour. Also, a more comprehensive index can be developed with additional data. Micro-scale data such as the presence of city furniture, shade coverage and seasonal greenery can contribute to adding more features to the walkability index.

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