Assessing Walkability in Sofia: A Multi-Metric Index for Pedestrian-Friendly Cities

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Abstract

Despite the growing interest in urban walkability, a significant gap remains in assessing pedestrian accessibility at the neighbourhood level in Sofia, Bulgaria. This study aims to bridge this gap by developing a comprehensive walkability index tailored to Sofia's urban environment. The index is constructed using ten key metrics that reflect six core aspects of pedestrian experience: connectivity, convenience, comfort, conviviality, coexistence, and commitment. The methodology employs geospatial analysis and computational modelling implemented in Python, leveraging libraries such as GeoPandas, Shapely, and NetworkX. The study assesses street connectivity using a link-to-node ratio, public transport coverage via shortest-path analysis, and network integration through the Pedestrian Route Directness Indicator (PRDI). Land use mix is evaluated using entropy-based calculations, while residential density considers household distribution within the built environment. Essential activities, pedestrian infrastructure, and convivial points are analysed based on proximity and spatial coverage. Traffic conditions are quantified through lane density, and the pedestrian-friendly network is assessed by mapping designated pedestrian-prioritized areas.

Results reveal spatial disparities in walkability across Sofia's neighbourhoods, with variations influenced by infrastructure availability, land use diversity, and traffic conditions. By visualizing normalized scores, the study identifies areas with inadequate pedestrian conditions, providing a framework for targeted infrastructure improvements. The findings contribute to urban planning by offering actionable insights to enhance pedestrian accessibility and promote sustainable mobility. This methodology is adaptable to other urban contexts, further advancing walkability research and policy development.

1. Introduction

Walkability has emerged as an important factor in urban planning, public health, and sustainable development. A high level of walkability is linked to various benefits, including improved public health through increased physical activity, reduced traffic congestion, lower carbon emissions, and stronger social interactions within local communities (Litman, 2010). These advantages highlight the importance of creating pedestrian-friendly environments in urban settings. Thus, there is growing research into methods for measuring walkability. This shows the need for reliable, data-driven indicators that allow for educated decisions and policy interventions.

Several approaches have been developed to assess walkability, incorporating both quantitative and qualitative methods (Southworth, 2005). Some studies use straightforward infrastructure counts, such as the presence of sidewalks and crosswalks, while others rely on more complex, multi-factor indices that consider street connectivity, land-use diversity, safety, and aesthetics (Ewing & Cervero, 2010). These varied methodologies reflect the complexity of walkability and the necessity of adapting measurement tools to specific contexts and research objectives. To address local variations, practitioners increasingly employ geospatial analysis and data-driven techniques, often using open data sources and computational tools to calculate walkability metrics.

Despite this growing interest, there remains a significant gap in walkability assessments at the neighbourhood level in Sofia, the capital of Bulgaria. To fill this gap, this study examines the city's walkability by means of a walkability index. The index is based on a cumulative score derived from ten key metrics that reflect six core aspects of pedestrian experience: connectivity, convenience, comfort, conviviality, coexistence, and commitment. Each metric is weighted and summed to generate the final walkability index for all neighbourhoods.

The primary objectives of the study can be summarized as follows:

- Develop a neighbourhood-level walkability index for Sofia comprising several metrics;
- Identify areas with inadequate pedestrian conditions, thereby establishing priorities for targeted infrastructure improvements;
- Provide suggestions and recommendations that can support planning and policymaking.

The study contributes to the expanding body of research on walkability assessment by offering an approach that is both context-specific and adaptable for broader urban environments. It extends our previous work on walkability analysis, introducing an Accessibility Index that evaluates residential access to POIs, incorporating diversity metrics such as the Shannon and Simpson indices (Petrova-Antonova, 2025).

The rest of the paper is structured as follows. Section 2 provides a background of the study and summarizes the related work. Section 3 is dedicated to the study area and data. Section 4 describes the methodology for the calculation of the walkability metrics and cumulative index. Section 5 presents the results and provides suggestions for policymakers. Finally, Section 6 concludes the paper and outlines the future work.

2. Background and Related Work

Walkability metrics provide a comprehensive evaluation of the urban environment regarding pedestrian accessibility, comfort, and convenience. The following section aims to broaden the audience's understanding of the metrics and show the credibility of these scores based on previous research.

Street connectivity is frequently measured through the link-to-node ratio, a widely accepted metric in urban studies. High connectivity promotes shorter routes, greater accessibility, and a more pedestrian-friendly environment. Grid-like Street layouts, as seen in traditional urban centres, often achieve efficient pedestrian and vehicular movement (Leão & Urbano, 2020). In addition, street connectivity impacts children walking to school. The higher connectivity, combined with low traffic exposure, significantly increased walking rates. Conversely, high connectivity, together with high traffic volumes, decreases walking (Giles-Corti et al., 2011). The presence and coverage of public transport refer to the accessibility and spatial distribution of transit systems within a city or region, including buses, subways, and trams. High coverage is associated with increased transit use, reduced traffic congestion, and lower greenhouse gas emissions. Wey and Chiu (2013) demonstrated that the accessibility of public transport within transit-oriented developments (TODs) promotes non-motorized modes of transportation like walking and cycling. TOD strategies prioritize high-density, mixed-use neighbourhoods around transit hubs to enhance coverage and accessibility. Such integration reduces travel times, promotes economic activity, and encourages active transportation modes (Muley et al., 2007).

Network integration refers to the degree to which a specific area's street network is interconnected. A key metric for evaluating network integration is the Pedestrian Route Directness Indicator (PRDI). PRDI provides insights into the efficiency of pedestrian routes, highlighting areas where indirect paths or poor integration may hinder walkability. It is applied in urban settings to evaluate how effectively street networks connect residential areas to essential amenities. Results show that higher directness values correlated with increased walking rates and reduced car dependency (Soltani, 2005). Diverse land uses within a neighbourhood significantly enhance its walkability. The entropy-based land use diversity metric captures the variety and balance of residential, commercial, and recreational spaces. Studies have shown that areas with higher land use mix scores have reduced travel distances for everyday activities, thus encouraging walking (Frank et al., 2006). Similarly, adults living in neighbourhoods with high land use mix walked up to 8% more daily than those in less diverse areas (Hajna et al. 2015). This highlights the importance of diverse destinations in promoting physical activity. The mixed-use zones provide economic and social benefits (Yang, 2008). High land use mix reduces the environmental impact of urban living, lowering vehicle miles travelled and increasing walking and cycling modes of transportation (Frank et al., 2006).

Residential density plays a significant role in creating active transportation and reducing vehicle dependency. Increased residential density is strongly associated with higher walking and public transit usage. Compact, high-density urban forms encourage more sustainable travel behaviours and contribute to reduced greenhouse gas emissions (Ewing and Cervero, 2010). Similarly, Wang et al. (2013) demonstrated that residential density is a vital determinant of physical activity levels, linking it to obesity prevention through active commuting and recreational walking. Urban planners often promote higher residential densities as part of compact city strategies to maximize land use efficiency and support transit-oriented development, creating vibrant, mixed-use neighbourhoods that encourage walking and reduce car dependency (Muley et al., 2007).

Proximity to essential amenities, such as grocery stores, cafes, parks, schools, and healthcare facilities, is a critical determinant of walkability. These amenities serve as frequent destinations for daily activities, and their accessibility significantly influences residents' travel behaviour and quality of life. This accessibility not only enhances walkability but also supports social interaction and community engagement by encouraging people to spend more time in local areas (Forsyth, 2015). In addition, accessible amenities enhance social equity by reducing travel burdens for low-income households who may lack access to private vehicles. The availability of pedestrian infrastructure refers to the presence and quality of facilities such as sidewalks, pedestrian crossings, pathways, and traffic-calming measures that enable safe and comfortable walking. High-quality pedestrian infrastructure improves public health, reduces traffic-related accidents, and fosters social interaction. Neighbourhoods with higher sidewalk coverage had significantly higher walking rates than those with discontinuous pedestrian networks (Handy et al., 2002). Ellis et al. (2016) further explored the impact of footpath quality and connectivity on physical activity levels. They found that areas with well-connected and high-quality pedestrian networks experienced increased rates of walking for both leisure and commuting purposes.

Convivial points, such as parks, plazas, cultural centres, libraries, sports facilities, and other community areas, encourage social interaction, citizen engagement, and a feeling of a sense of belonging. They significantly enhance urban life by providing opportunities for informal socialization, physical activity, and cultural engagement, which contribute to both mental and physical well-being. Similarly, green and open spaces within urban environments improve mental health by reducing stress and promoting relaxation, making them essential components of walkable neighbourhoods (Lee & Maheswaran, 2011). The convivial points also play a crucial role in promoting equity and inclusivity. They promote physical activity, as neighbourhoods featuring parks and sports facilities report higher levels of walking and exercise among residents.

Extensive traffic significantly reduces pedestrian affinity, making urban environments less walkable and less appealing for walking. It not only poses physical dangers to pedestrians but also creates psychological barriers by diminishing the comfort of walking. Higher numbers of lanes and increased vehicular flow are associated with higher traffic noise, emissions, and safety risks. Appleyard et al. (1981) proved that traffic volume negatively impacts pedestrian activity and social interactions, emphasizing that streets dominated by cars experience reduced liveability and community engagement. Reducing traffic lanes and decreasing vehicle speeds through design interventions has been shown to enhance the pedestrian experience and promote walking. Streets designed with traffic-reduction measures, such as narrower lanes, lower speed limits, and raised crosswalks, improve pedestrian safety and encourage walking by creating a more human-scaled environment (Ewing & Dumbaugh, 2009).

A pedestrian-friendly network is a system of well-connected streets and pathways designed to prioritize walking by enhancing accessibility, safety, and comfort for pedestrians. It often features elements such as continuous sidewalks, traffic-calming measures, pedestrian-only zones, safe crossings, and mixed-use development, promoting active mobility. It has been shown that highly connected street grids with frequent intersections enable shorter travel distances and easier navigation for pedestrians. Such designs reduce barriers to walking and encourage active transportation (Ewing & Cervero, 2010). The neighbourhoods with integrated and continuous sidewalks experienced higher levels of walking compared to those with fragmented or poorly maintained pedestrian infrastructure (Handy et al., 2002).

Traffic-reducing measures not only improve pedestrian safety but also create more vibrant street environments that encourage social interaction (Dumbaugh & Li, 2010).

3. Study Area and Data

This section describes the study area and data used for the analysis of the neighbourhood.

3.1 Study Area

Sofia, Bulgaria's capital city, has witnessed rapid urbanization over recent decades due to a growing population and expanding economic opportunities. This has led to the development of new residential suburbs, where housing construction often precedes the establishment of essential infrastructure. Basic amenities such as kindergartens, well-structured road networks, and continuous sidewalks are frequently lacking or insufficient. As a result, many residents struggle with limited access to essential services and safe pedestrian pathways (Sofiaplan, 2023).

The absence of comprehensive urban infrastructure in these newly developed areas not only reduces walkability but also exacerbates broader social and environmental challenges. Incomplete sidewalks and missing pedestrian crossings force residents to rely on private vehicles, which contributes to increased traffic congestion, emissions, and safety risks (Ewing, 2010). Additionally, the lack of public spaces, playgrounds, and local amenities can weaken community connections and limit opportunities for physical activity and social interaction (Southworth, 2005). Addressing these problems is essential to ensure the long-term liveability of Sofia's neighbourhoods.

3.2 Data Collection and Enrichment

The first step in developing the walkability index is collecting the necessary geospatial data. Table 1 describes the corresponding datasets, all of which are provided in GeoJSON format.

Dataset	Description
Neighbourhoods' boundaries	Polygons that define the administrative or planning boundaries of each neighbourhood.
City boundaries	A polygon representing the official administrative city's boundary
Land use	Polygons, classified by how the land is utilized, such as residential, commercial, industrial, etc.
POIs	Locations of various amenities — health centres, kindergartens, mobility infrastructure, entrances of parks, schools, sports facilities, etc.
Street network	Line segments of road infrastructure, typically including major highways, arterial roads, and local streets, with attributes like road type or speed limits.
Pedestrian network	Line segments, including sidewalks and footpaths, designed for pedestrians.
Buildings	Polygons representing built structures, including area and location, floor count, apartment count, type of building.

Table 1. Study datasets.

The street network dataset is enriched by including the number of road lanes for each street segment. This is implemented by loading geospatial data for street centrelines and road polygons using GeoPandas package in Python. A key part of the workflow involves cleaning geometries to ensure validity using Shapely's make_valid function. For each polygon, the Python script calculates an average width by sampling random points within the polygon and estimates their distances to the nearest boundary. The average distance doubled to represent the polygon's width, is then used to infer the number of lanes based on a specified lane width, with a default value of 3 meters per lane. A spatial join is performed to match polygons with street segments, assigning the inferred lane counts to the intersecting streets.

A new dataset is created that contains pedestrian-friendly streets. Streets that are designated as "pedestrian-friendly" need to match the following criteria:

- Traffic-calming measures in place
- Pedestrian-only or reduced vehicle dominance
- Cultural, social landscaping and street activity
- 30 km/h zones designated by the municipality

The abovementioned measures need to be either present on street level or in the immediate vicinity of a given street (50m).

3.3 Data Preprocessing

A data preprocessing script prepares localized, neighbourhood-specific datasets in a single automated workflow. First, it reads a GeoJSON file containing all neighbourhoods' polygons and a collection of other GeoJSON files (e.g., roads, pedestrian networks, land use for the entirety of Sofia) stored in a dictionary. Next, the sanitize_filename function ensures that each neighbourhood's name is stripped of characters that could cause file-system errors, allowing the creation of valid folders and file names. The main function, filter_data_by_neighbourhood, then loops through each neighbourhood, extracts its geometry, and saves it as a GeoJSON file within a newly created folder. For each dataset in the dictionary, the script uses the neighbourhood's geometry to filter out features that either lie fully within or intersect the neighbourhood boundaries, depending on the dataset type. These filtered subsets are saved in GeoJSON files.

4. Methodology

This section provides a description of walkability metrics, explaining their implementation in Python and weighting with respect to the cumulative walkability index. The walkability index is calculated based on metrics described by Cambra (2012) as follows: street connectivity, presence and coverage of public transport, network integration, land use mix, residential density, essential activities, availability of pedestrian infrastructure, convivial points, traffic and pedestrian-friendly network.

4.1 Street Connectivity

The Street Connectivity metric assesses the efficiency and interconnectivity of a street network by calculating the so-called "link-to-node" ratio, which is the relationship between the number of street segments (links) and intersections (nodes). A well-connected network, characterized by higher connectivity ratios, facilitates movement and accessibility, which are essential for creating pedestrian- and transit-friendly environments. The metric evaluates the ratio of street segments to intersections, with a base value of 1.0 and a goal value of 2.5, representing a highly connected street network (e.g., regular grids with four-way intersections). Values in the range of 1.4 to 1.8 are considered acceptable.

The street connectivity calculation begins by merging individual street segments (LineStrings or MultiLineStrings) into unified geometries using a unary union operation, ensuring that extraneous or duplicate segment edges are consolidated. Next,

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the method identifies intersection points by iterating over pairs of merged street geometries and determining where they intersect as single points or collections of points. Each unique intersection is stored as a node in a GeoDataFrame, allowing the method to derive a link-to-node ratio, where "links" represent individual street segments and "nodes" represent intersection points. To avoid division errors in neighbourhoods lacking intersections, the method returns a default value when no valid nodes are found. Finally, the ratio is capped between 1.0 and 2.5, and an optional visualization step plots the street network along with intersection nodes for a clearer interpretation of connectivity patterns.

4.2 Presence and coverage of public transport

This metric assesses the extent to which public transport stops serve the surrounding street network within typical walking distances (e.g., 400 m or 800 m). First, the script creates a uniform node-based representation of the street network by sampling points along each street segment at fixed intervals and then linking consecutive points into edges. Every public transport stop is snapped to the nearest street line, and from that point, a shortest-path search (Dijkstra's algorithm) identifies all nodes and edges reachable within the specified distance cutoff. The proportion of street segments considered "covered" by reachable nodes is then calculated by comparing the length of covered edges to the total street length. This coverage value is capped at a maximum of 100% and is produced for multiple distance thresholds to capture how well public transport provision meets different walking-distance criteria. The method includes a visualization component that plots the street network, public transport stops, and covered segments to illustrate coverage spatially. The implementation uses GeoPandas and Shapely for geospatial data manipulation, networkx for graph-based network analysis, and Matplotlib for visualization.

4.3 Network Integration

This metric evaluates the connectivity of a neighbourhood using the Pedestrian Route Directness Indicator (PRDI). This indicator measures the ratio between the street network distance and the straight-line distance from a central point to locations at an 800-meter buffer. A value close to 1 indicates direct connectivity (more favourable for pedestrians), while a value closer to 2 suggests indirect paths, requiring pedestrians to walk longer distances compared to the straight-line distance.

First, the street geometries are converted into a graph where each point in a LineString becomes a node, and edges connect adjacent nodes along each street. A central reference point is derived from the neighbourhood's boundary, and eight sample points are generated at regular angular intervals around it, capped by the neighbourhood boundary if necessary. For each sample point, the code measures the straight-line distance to the central point and contrasts that with the network route distance computed via shortest-path analysis. The ratio of these two distances averaged across all sample points, represents the "pedestrian route directness. The final score is capped to avoid extreme outliers and may be visualized by plotting both the direct lines and the street-based paths for each sample point.

4.4 Land Use Mix

The Land Use Mix metric assesses the diversity of land uses within a given neighbourhood—an important factor for walkability—using a standardized entropy-based formula that ranges from 0 (only one land use type) to 1 (equal distribution of all categories). First, each polygon in the dataset is mapped to one of ten predefined categories —"High-Density Residential Areas," "Medium- and Low-Density Residential Areas," "Transportation and Infrastructure," "Manufacturing and Industrial Areas," "Public and Recreational Spaces," "Agricultural and Pastoral Lands," "Natural and Semi-Natural Areas," "Water Bodies and Related Areas," "Unused or Isolated Areas," and "Mixed-Use or Transitional Areas"—through the map_land_use_to_group function. The total area of the neighbourhood is then computed, and the proportion p_i of each category's area is used in the entropy calculation as follows:

$$H = \frac{-\sum_{i=1}^{k}(p_i \ln(p_i))}{\ln(k)} \quad (1)$$

where k is the number of unique categories. The main function, calculate_land_use_mix, centralizes these operations, ensuring values remain within the 0–1 range and defaulting to 0 when no valid data is present. Higher entropy values signify greater land use diversity.

4.5 Residential Density

The Residential Density (RD) metric evaluates the number of residential units within a specific area to assess walkability. Higher RD often leads to a reduction in the need for long travel distances, as it increases the number of potential origins and destinations within a neighbourhood. The metric is calculated as gross RD, which is the ratio of the total number of households to the study area's surface area (in hectares). Performance levels range from a base value of 40 (representing quasi-urban density) to a goal value of 200 (high urban density). While higher RD can improve walkability by reducing walking distances, very high densities might overload pedestrian infrastructure, potentially decreasing user satisfaction.

The gross RD is calculated for a given study area by estimating the number of households within residential buildings. The calculation starts by determining the total households for each building. For single-family buildings, the number of households is set to one. For multi-unit buildings, the estimation considers factors such as the number of apartments. If this information is not available, then the RD is calculated based on the Area of the Building (AB), Floor Cout (FC), Common Area Reduction (CA), Average Area per Person (AAP) needed and Average Size of a Household (ASH) as follows:

$$RD = \frac{AB \times FC \times CAR}{AAP} / ASH \quad (2)$$

where CA = 0.8, AAP = 30 sq. m and ASH = 2.2 people. The abovementioned parameters are based on a previous analysis by the Ministry of Regional Development and the National Statistical Institute in Bulgaria. After estimating the total number of households in all buildings, the total study area in hectares is calculated and the residential density as the ratio of households to the study area's size is evaluated.

4.6 Essential Activities

The Essential Activities metric evaluates pedestrian accessibility to essential services such as groceries, cafes, restaurants, and other frequently visited amenities. It emphasizes the importance of nearby activities that encourage non-commuting walking trips, contributing to higher pedestrian activity. The metric calculates the percentage of street segments within a 400-meter walking distance from activity locations using the street network. The goal value is 1 (100% coverage), while the base value is 0.

Initially, the street segments covered by a 400-meter walking distance buffer from essential activity locations are identified. The calculate_essential_activities function orchestrates the process, ensuring that both the street network (streets_gdf) and essential activity points (other_pois_gdf) are utilized effectively. The street network is processed using the merge_street_segments function to ensure continuous segments, facilitating accurate coverage calculations. The create_graph_from_streets function creates a graph representation of the street network, where nodes represent street endpoints and edges represent street segments. This graph is essential for determining the street segments reachable within the buffer distance. For each essential activity location, the find_nearest_node function identifies the nearest node in the graph, and Dijkstra's algorithm is used to compute the reachable nodes within the 400-meter buffer. The edges (street segments) associated with these nodes are then flagged as covered. The calculate_essential_activities_coverage function calculates the total length of covered street segments and divides it by the total street network length to determine the coverage percentage. Finally, the results are visualized by essential_activities_coverage function, displaying the full street network, covered segments, and essential activity locations on a map. A capped percentage is obtained, ensuring values remain between 0 and 1. The libraries such as GeoPandas and Shapely are used for geospatial processing, networkx for graph-based operations, and Matplotlib for visualization.

4.7 Availability of Pedestrian Infrastructure

The Availability of Pedestrian Infrastructure metric measures the extent of sidewalks within a given pedestrian network, assessing their availability. It emphasizes the comfort of the pedestrian infrastructure, such as standard sidewalks that are elevated and paved or nonstandard sidewalks that are separate from the road environment. The ratio of the total length of pedestrian network segments with sidewalks to the total pedestrian network length is calculated. A base value of 0.5 (indicating 50% coverage) is considered acceptable, with a goal value of 1 (100% coverage) as the target. It is assumed that in an ideal scenario, each street segment should have at least one sidewalk.

The pedestrian network dataset is used to compute the sidewalk coverage. The segments are distinguished as either having sidewalks or not, based on their type attribute (e.g., "Тротоар" for sidewalks or "Алея с настилка" for paved alleys). The total length of all pedestrian segments is calculated, as well as the total length of segments classified as having sidewalks. The availability score is determined by dividing the total sidewalk length by the total pedestrian network length. A visualization of the pedestrian network is performed, displaying segments with sidewalks in green and those without in red, offering a clear spatial representation of the sidewalk distribution. The final output includes the raw availability score and a score ranging from 0.5 to 1, reflecting whether the infrastructure meets the metric's defined targets.

4.8 Convivial Points

The Convivial Points metric measures the presence and coverage of social interaction spaces within a study area. In this study, convivial points are represented by sport, culture and park/garden POIs. The convivial points within the area are identified, and the proportion of street network length covered by a 400-meter walking buffer around these points is calculated. This proportion is expressed as a percentage of the total street network length. The base value for this metric is 0 (no coverage), while the goal value is 1 (100% coverage).

The extent of the street network accessible within a 400-meter walking distance from convivial points is determined. The street segments are merged into simplified geometries using Shapely's line merge and unary_union functions. A graph representation of the street network is constructed using networkX Python package, where nodes represent points along street geometries and edges represent the connections between them. The convivial points are identified by extracting sport facilities, cultural points, and park entrances, and combining them into a single GeoDataFrame. For each point, the set of street network nodes reachable within the buffer distance is calculated using Dijkstra's algorithm. These nodes represent the so-called "covered" portion of the street network. The total length of covered street segments is calculated by aggregating the lengths of segments associated with the covered nodes. This length is divided by the total street network length to compute the coverage percentage.

4.9 Traffic

The Traffic metric evaluates the impact of road traffic on walkability by considering it a negative factor. This metric specifically assesses traffic through the number of traffic lanes, as more lanes correlate with higher traffic volumes, speeds, and public space consumption. A weighted average of traffic lanes across the street network is calculated, using the street segment length as the weight. The base value for this metric is 4, representing an average of 2x2 lane streets, while the goal value is 0, representing no traffic flow.

The necessary attributes, such as the number of lanes and street segment length are checked for availability in the GeoDataFrame. The weighted contribution of each street segment to the total number of lanes is calculated by multiplying the value of the lane by the segment length. The total weighted number of lanes and the total street network length are calculated. The traffic metric is computed as the ratio of these two values, representing the weighted average number of lanes across the entire street network. If no data is available, the function defaults to a base value of 4. A visualization is performed on a map, representing the number of lanes for each street segment using a gradient colour scheme, providing a spatial understanding of traffic lane distribution. The result is returned as a raw metric value and a capped value between the base (4) and goal (0).

4.10 Pedestrian Friendly Network

The Pedestrian Friendly Network metric calculates the proportion of a neighbourhood's street network that is specifically designated as pedestrian-friendly, providing an indication of how well a neighbourhood accommodates walking. First, the total length of streets in the neighbourhood is calculated, and then an intersection operation isolates those segments that also appear in a city-wide dataset of pedestrian-friendly streets (streets with traffic-calming measures in place, pedestrian-only or reduced vehicle dominance, cultural, social landscaping and street activity, 30 km/h zones designated by the municipality). The ratio of this "pedestrian-friendly" street length to the total street length yields a coverage score between 0 and 1, with higher values denoting better pedestrian infrastructure. The method returns 0 if the neighbourhood or pedestrian-friendly dataset is empty and visualizes this coverage by highlighting the relevant segments on a map.

4.11 Metrics' Output and Weights

It is important to note that two values for each metric are calculated: the first one is the raw score, and the second one is the capped score between the base and goal value provided by Cambra (2012) for each metric. Upon calculating the tuple score (raw, capped) for each metric, individual scores are normalized between base and goal values. Min-max normalization has been applied, using the following formula:

$$x^i = \frac{x - base_{value}}{goal_{value} - base_{value}} \times 100 \quad (3)$$

After that, the scores are weighted and summed to achieve a neighbourhood's walkability index. Table 2 lists the weights of the metrics, which are aligned with the Spatial Development Act of Bulgaria (Ministry of Regional Development, 2023) and defined by urban planning experts from Sofiaplan, a municipal enterprise responsible strategic spatial planning of Sofia City and Municipality. Context-specific adjustments of the weights can be made in case of replication of the study to other cities and regions.

Metric	Weight
Street connectivity	0.0555
Presence and coverage of public transport	0.0556
Network Integration	0.0555
Land use mix	0.0555
Residential density	0.0555
Essential activities	0.0556
Pedestrian infrastructure availability	0.1667
Convivial points	0.1667
Traffic	0.1667
Pedestrian-friendly network	0.1667

Table 2. Weights of metrics for walkability index calculation.

The final walkability index per neighbourhood is calculated using the following formula:

$$Walkability\ Index = \sum_{i=1}^{10} (w_i \times S_i) \quad (4)$$

where w is the weight, and S is the score of any given metric.

5. Results

This section presents the obtained results, visualising them on maps and discussing the main findings. Suggestions for policymakers are also outlined.

5.1 Results Visualisation and Discussion

The results of this study show the cumulative walkability index and its constituent metrics for each neighbourhood in Sofia. The raw scores are normalized between the base and goal values, providing a representation of the neighbourhood's performance relative to the defined thresholds. This approach ensures that even neighbourhoods with extreme values are represented proportionally, reflecting their relative standing within the study area. Figure 1 visualises the cumulative walkability index.

The capped scores are constrained within the base and goal values before normalization. This ensures that extreme values, whether due to data anomalies or unique circumstances, do not significantly affect the final scores. By limiting the scores to a standardized range, the capped values provide a balanced and comparable representation of walkability across neighbourhoods. At the same time, the normalisation can still produce outliers in cases where data availability is limited or specific neighbourhood characteristics, such as park zones, deviate from standard urban environments.

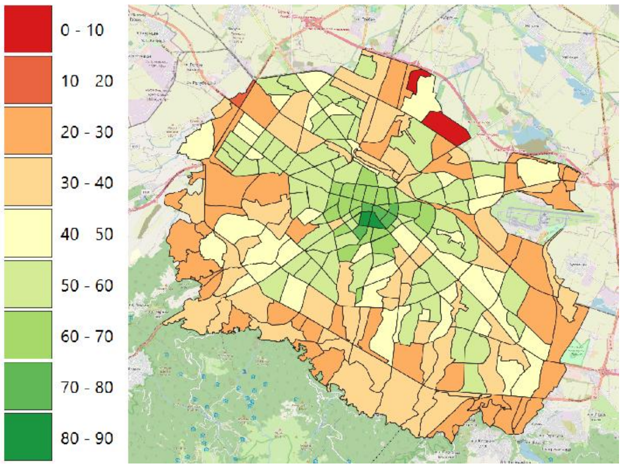
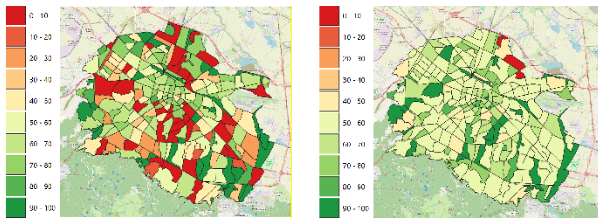


Figure 1. Cumulative walkability index.

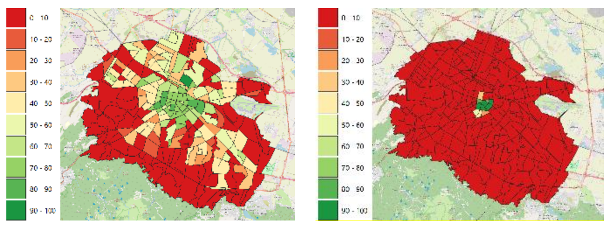
Separate visualizations for each metric are prepared to compare the neighbourhood more deeply. The walkability analysis of Sofia revealed disparities in neighbourhood scores across various metrics. Some neighbourhoods scored high on certain dimensions, reflecting well-developed infrastructure in these areas. However, other neighbourhoods, especially those located in peripheral regions, showed suboptimal results due to poorer infrastructure or a lack of data. Figure 2 shows the results from the network integration (a) and street connectivity (b) analysis.



(a) (b)

Figure 2. Network integration and street connectivity metrics.

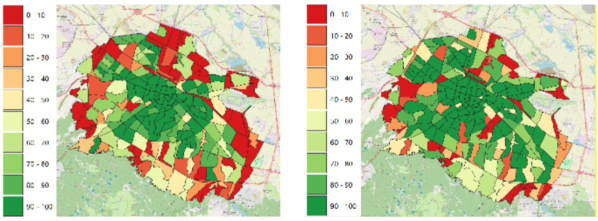
Figure 3 presents the results from the availability of pedestrian infrastructure (a) and pedestrian-friendly network (b) analysis.



(a) (b)

Figure 3. Pedestrian infrastructure and pedestrian-friendly network metrics.

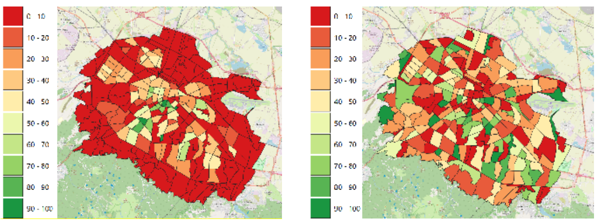
Figure 4 shows the results from the convivial points (a) and essential activities (b). The analysis shows an imbalance in the presence of pedestrian infrastructure and essential activities. Neighborhoods with low residential densities frequently lacked the essential amenities necessary for pedestrian-friendly environments, such as grocery stores, bakeries, and cafes. This could be attributed to urban planning challenges in accommodating both residential and commercial activities in the same zones. Metrics such as street connectivity and pedestrian-friendly network coverage showed a wide range of values across Sofia, pointing to the uneven distribution of walking infrastructure. While some central neighbourhoods showed high street connectivity and integration, peripheral neighbourhoods lagged behind, which shows historical and geographic development patterns. According to the traffic metric, high scores indicated significant car presence and a lack of pedestrian-friendly planning. Efforts to reduce the number of traffic lanes or implement low-speed zones could substantially improve these areas.



(a) (b)

Figure 4. Convivial points and essential activities metrics.

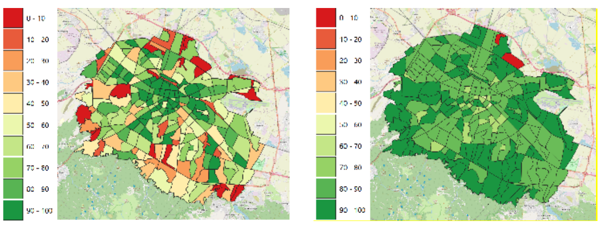
Figure 5 visualises the results from the residential density (a) and land use mix (b) analysis.



(a) (b)

Figure 5. Residential density and land use mix metrics.

Figure 6 shows the results from the presence and coverage of public transport (a) and traffic (b) analysis.



(a) (b)

Figure 6. Presence and coverage of public transport and traffic metrics.

Some neighbourhoods in Sofia, especially parks, green areas, peripheral regions or industrial sites, lack the types of infrastructure that the metrics in this study measure, resulting in skewed scores. For instance, park areas inherently lack certain features related to residential density or essential activities, which are critical for high walkability scores. As a result, these zones displayed disproportionately low scores, even though they might contribute positively to overall urban walkability by offering open and green spaces. Additionally, green/park zones often have minimal roads, public transport stops, POIs, facilities that relate to conviviality, etc. This leads to extremely low values in almost all metrics, as they lack both everyday amenities and land-use diversity. Conversely, some peripheral areas feature sparse, sporadic roads that do not intersect, which yields an artificially high link-to-node ratio for the Street Connectivity metric. Because there are few nodes, the ratio of segments to intersections often approaches or exceeds desirable ranges. The residential density metric further illustrates discrepancies where industrial zones and certain outlying areas fail to reach even the base value of 40 households per hectare, creating disproportionately low scores in those zones. These anomalies highlight how specialized land uses, parks, large industrial tracts, and peripheral edges, can distort multiple metrics designed around more mixed-use, residential, or transit-served conditions.

5.2 Suggestions for Policymakers

Improving walkability in Sofia requires a coordinated strategy that addresses the infrastructural problems identified in different neighbourhoods. First, policymakers should prioritise pedestrian infrastructure upgrades in areas with low sidewalk coverage and limited traffic-calming measures, as research shows that well-connected, well-maintained sidewalks significantly increase walking rates (Handy et al., 2002). Second, strengthening public transport integration, especially in peripheral districts, can reduce private vehicle use and congestion, since a reliable public transit system within walking distance encourages more residents to walk (Wey & Chiu, 2013). Third, promoting mixed land use development through zoning reforms and incentives can create balanced, compact neighbourhoods that shorten trip distances for daily necessities and thus encourage walking (Frank et al., 2006). Additionally, municipalities should aid essential amenities and convivial points, and support the establishment of grocery stores, childcare facilities, cultural venues, and other key services in underserved areas (Forsyth, 2015). Further, traffic reduction measures such as narrower lanes and lower speed limits can enhance safety and encourage a more human-focused environment (Ewing & Dumbaugh, 2009). Also, building a pedestrian-friendly network of walkways and safe crossings, even in neighbourhoods that currently have fragmented sidewalks, can close gaps in connectivity (Muley et al., 2007). Ongoing data collection and monitoring of geospatial information will allow the municipality to refine walkability assessments and respond to evolving needs (Litman, 2010).

To ensure practical implementation, these recommendations should be prioritized based on cost-effectiveness and impact. Low-cost, high-yield improvements—such as enhancing crossings, adding signage, and applying traffic-calming measures—can be targeted first in neighbourhoods with the lowest walkability scores. Integrating walkability upgrades into existing infrastructure projects can reduce costs, while designating walkability improvement zones based on the index can help focus efforts. A phased approach, starting with pilot interventions in both central and peripheral areas, would allow for gradual scaling and resource-efficient implementation.

6. Conclusion and Future Work

This study evaluates the walkability of Sofia's neighbourhoods by constructing a multi-metric index that produces a cumulative score that provides insight into the liveability of Sofia's neighbourhoods. Each metric sheds light on urban problems and opportunities for future development. The findings underscore that neighbourhoods in Sofia vary considerably in terms of infrastructure development, proximity to amenities, and urban form, with central districts often performing better than peripheral ones. While some areas lack essential pedestrian facilities, resulting in lower scores, others have relatively high street connectivity yet remain limited in other aspects, like land use diversity. The index serves as evidence to identify priority zones for improvement by distinguishing neighbourhood-specific challenges and strengths.

To enhance the robustness of the findings, it is important to recognise that data limitations, especially in peripheral neighbourhoods and specialised land-use zones such as parks and industrial areas, may introduced uncertainties in the walkability scores. These limitations could lead to an underestimation or overgeneralization of walkability in less-documented areas. Future analyses will aim to address these issues by incorporating data quality assessments to assess the reliability of different input sources and conducting sensitivity analyses to understand how variations in data coverage influence the index results. These steps will help ensure more accurate, equitable, and defensible evaluations across all neighbourhood types.

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