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Developing an integrated framework for walkability assessment: A case study of Çankaya's urban mobility

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Abstract

Despite increasing recognition of walkability's importance in sustainable urban planning, no integrated framework exists for its assessment and improvement. Previous approaches have not mathematically evaluated optimal design criteria, showing the need for a new strategy to systematically enhance pedestrian environments. This study proposes an integrated strategy combining two techniques – spatial network analysis and design-multivariate optimisation – to address this inefficiency. In the first step, spatial network analysis was used to classify walkability levels as high, medium, or low, with the low levels identifying pedestrian routes in need of improvement. In the second step, a design-multivariate optimisation procedure was applied to mathematically derive the best design criteria by enhancing key walkability factors. The study examines 117 neighbourhoods in Çankaya, Turkey, a densely populated and mixed-use urban district. Given the importance of walkability in such areas, the research aims to support local government decision-making, by providing valuable insights for urban planning and development. Results indicate high walkability levels in the district's central areas but low walkability and connectivity between the centre and the eastern section. In the second phase, 20 streets were selected for further analysis, with data structured into a design matrix. Expert response to this matrix was used for multivariate optimisation, employing a second-order quadratic model to determine the optimal walkability design criteria. Findings highlight the value of combining and integrating network analysis with optimisation techniques to generate evidence-based solutions in urban planning. The proposed strategy offers practical recommendations for enhancing pedestrian infrastructure and establishing standardised design criteria, contributing to more sustainable, accessible, and pedestrian-friendly urban environments.

Keywords: Walkability, network analysis, design-multivariate optimisation, pedestrian, urban design

ONTWIKKELING VAN 'N GEÏNTEGREERDE RAAMWERK VIR STAPBAARHEIDSASSESSERING: 'N GEVALLESTUDIE VAN ÇANKAYA SE STEDELIKE MOBILITEIT

Ten spyte van die toenemende erkenning van die belangrikheid van stapbaarheid in volhoubare stedelike beplanning, bestaan daar geen geïntegreerde raamwerk vir die assessering en verbetering daarvan nie. Vorige benaderings het nie die optimale ontwerp-kriteria wiskundig geëvalueer nie, wat die behoefte aan 'n nuwe strategie toon om voetgangeromgewings sistematies te verbeter. Hierdie studie stel 'n geïntegreerde strategie voor wat twee tegnieke kombineer – ruimtelike netwerkontleding en ontwerp-multivariate optimalisering – om hierdie ondoeltreffendheid aan te spreek. In die eerste stap is ruimtelike netwerkontleding gebruik om stapbaarheidsvlakke as hoog, medium of laag te klassifiseer, met die lae vlakke wat voetgangerroetes aandui wat verbeter moet word. In die tweede stap is 'n ontwerp-multivariate optimaliseringsprosedure toegepas om die beste ontwerp-kriteria wiskundig te bepaal deur sleutel-stapbaarheidsfaktore te verbeter. Die studie ondersoek 117 woonbuurte in Çankaya, Turkye, 'n digbevolkte en gemengde stedelike distrik. Gegewe die belangrikheid van stapbaarheid in sulke gebiede, is die doel van die navorsing om plaaslike regeringsbesluitneming te ondersteun deur waardevolle insigte vir stedelike beplanning en ontwikkeling te bied. Resultate toon hoë stapbaarheid in die sentrale dele van die distrik, maar lae stapbaarheid en verbinding tussen die sentrale en die oostelike gedeelte. In die tweede fase is 20 strate gekies vir verdere ontleding, met data gestruktureer in 'n ontwerpmatriks. Deskundige reaksie op hierdie matriks is gebruik vir multivariate optimalisering, deur 'n tweede-orde kwadratiese model toe te pas om optimale stapbaarheidsontwerp-kriteria te bepaal. Bevindings beklemtoon die waarde van die kombinasie en integrasie van netwerkontleding met optimaliseringstegnieke om bewysgebaseerde oplossings in stedelike beplanning te genereer. Die voorgestelde

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strategie bied praktiese aanbevelings vir die verbetering van voetgangerinfrastruktuur en die vestiging van gestandaardiseerde ontwerpkriteria, wat bydra tot meer volhoubare, toeganklike en voetganger-vriendelike stedelike omgewings.

HO THEHA MORALO O KOPANETSOENG OA TEKOLO YA TSAMAISO EA MAOTO: THUTO YA MAEMO HO TSAMAISO EA MOTSE EA ÇANKAYA

Leha ho ntse ho eketseha kananelo ea bohlokoa ba bokhoni ba ho tsamaea ka maoto ho rulaganyo ya metse e tsitsitseng, ha ho so be le moralo o kopanetsoeng bakeng sa ho lekola le ho ntlafatsa maemo ao. Mekhoa e fetileng ha e a ka ea hlahloba ka tsela ya dipalo kriteria e loketseng bakeng sa moralo, e bontšang tlhokahalo ea leano le lecha ho ntlafatsa tikoloho bakeng sa maoto ka mokhoa o hlophisitsoeng. Thuto ena e hlahisa leano le kopanetsoeng le kopanyang mekhoa e 'meli: tlhahlobo ya marangrang a sebaka le "multivariate optimisation" bakeng sa moralo. Mohato oa pele o sebelitse tlhahlobo ya marangrang a sebaka ho hlopha maemo a tsamaeo ka maoto e le a phahameng, a mahareng kapa a tlase, moo a tlase a bontšang ditsela tse hlokang ntlafatso. Mohato wa bobedi o sebelitse "multivariate optimisation" ho fumana ka dipalo kriteria e ntle ka ho fetisisa, ka ho matlafatsa lintlha tsa bohlokoa tsa tsamaeo ka maoto.Thuto e shebile dibaka tse 117 motseng oa Çankaya, Turkey, o nang le baahi ba bangata le ts'ebeliso e fapaneng ya sebaka. Ka lebaka la bohlokoa ba bokhoni ba ho tsamaea ka maoto dibakeng tse joalo, sepheo sa patlisiso ke ho thusa mmuso wa lehae ka bohlale bo thusang rulaganyo ya metse. Diphetho di bontsha maemo a phahameng a tsamaeo karolong e bohareng empa a tlase pakeng tsa bohareng le bochabela. Mohato wa bobedi o khethile ditsela tse 20 bakeng sa tlhahlobo e tebileng, moo data e ileng ya hlophiswa ka matrix ya moralo. Karabelo ya litsebi e sebelisitsoe ho etsa optimisation ka mohlala wa dipalo wa quadratic wa boemo ba bobedi. Diphetho di totobatsa bohlokoa ba ho kopanya tlhahlobo ya marangrang le "optimisation" ho fana ka ditharollo tse thehiloeng bopaki bakeng sa rulaganyo ya metse. Leano le hlahisitsoeng le fana ka dikhothaletso tse sebetsang bakeng sa ntlafatso ya ditsela tsa maoto le kaho ya melao e lekanang ya moralo, ho ntshetsapele metse e tsitsitseng, e fumanehang habonolo, le e nang le tikoloho e loketseng maoto.

1. INTRODUCTION

Human mobility, which refers to the processes of spatial relocation undertaken by individuals or groups within a specific time frame, also represents the interactions between people and the urban environment, making it a crucial component of more inclusive and sustainable cities (Barbosa *et al*., 2018). Therefore, as cities have grown, the focus of urban design and policymaking has shifted to human mobility. On the other hand, contemporary urban mobility is characterised by issues such as traffic congestion, pollution, time loss, noise, and inefficiency in capacity and space utilisation, all of which hinder the scale required for a modern urban economy to function efficiently (Ceder, 2021). In this context, urban mobility has a key role in making cities more liveable, accessible, equal, and resilient, by promoting sustainable trips through public transport and active modes such as walking and cycling. This awareness determined the rise of various initiatives such as the concept of the 15-minute city, which is based on a proximity-oriented approach and the redistribution of urban amenities at the district scale (Ermagun, Janatabadi & Witlox, 2025; Gaglione *et al*., 2021; Gaglione, Gargiulo & Zucaro, 2022). This approach aims to provide urban amenities that must be accessed within a short distance in a residential area (Graells-Garrido *et al*., 2021). This situation has led to an increase in research on the relationship between human mobility and the physical environment (TRB & IM, 2005; Vojnovic *et al*., 2006; Cerin *et al*., 2007). Analyses of urban human mobility facilitate the comprehension of the spatial distribution of human activities (Huang *et al*., 2015) and the spatial interactions among urban regions. Moreover, these analyses contribute to uncovering the underlying driving forces of human movements within cities and the complex spatiotemporal structure of urban environments (Zhang & Li, 2024).

The walkability concept bridges academic research on urban walking and personal mobility as well as policy and planning processes. The term 'walkability' describes the extent to which a street's environment and form support and encourage walking (Southworth, 2005; Li, Yabuki & Fukuda, 2023). Walkability has emerged as a comprehensive conceptual framework encompassing a wide range of variables used in studies conducted at different scales and for various purposes. Given its broad scope, walkability should be understood not merely as a technical metric, but also as a dynamic discourse shaped around the built environment and urban life. For example, Speck (2013) states that walkability refers to urban spaces that are useful, safe, comfortable, and interesting (Shields *et al*., 2023).

From another viewpoint, walkability is a functional feature to be considered in urban planning and is the foundation of a sustainable city (Forsyth & Southworth, 2008). From this perspective, the built environment is considered a critical factor in promoting walking (Gomez *et al*., 2010; Moran *et al*., 2017; Cheng *et al*., 2019; Marquet *et al*., 2022; Kim, Yeo & Lim, 2024). Like cycling, walking is a 'green' mode of transport that not only reduces congestion but also has a low environmental impact and saves energy without air and noise pollution. Trips to work, school, or shopping can be more than simply a purely utilitarian method of travel and can have both social and recreational value. In addition, it is a socially equal mode of transport available to most of the population between classes, including children and the elderly. Briefly, human mobility and walkability are of great importance for the quality of urban life. For these reasons, researchers created various planning and design lists to improve walkability.

A significant part of the planning studies focuses on the distribution of land use, quality of construction and environment, high density, access to local services, and equal transportation models (Banister & Hickman, 2006; Banister, 2008; Orellana & Wachowicz, 2011; Zook *et al*., 2012; Lerman, Rofè & Omer, 2014; Dempsey, Brown & Bramley, 2012; OECD, 2012;

Marquet & Miralles-Guasch, 2015; Schoeman, 2015).

Researchers have systematically classified walkability evaluation criteria, considering factors such as accessibility, safety, comfort, and pleasantness (Alfonzo, 2005), as well as aesthetic elements such as imageability, openness, human scale, transparency, and complexity (Ewing & Handy, 2009). Mesoscale walkability indices based on objective variables such as street accessibility have been developed and widely applied (Frank *et al*., 2010; Witten *et al*., 2012; Rundle *et al*., 2019). However, these indices fail to adequately capture microscale urban features such as sidewalk conditions, and subjective aspects such as street attractiveness (Bivina & Parida, 2019; Zhou *et al*., 2019). Some studies focus on the implementation of best practices for urban regeneration, constructing a matrix that categorises these practices based on their impact on urban competitiveness (Gargiulo & Sgambati, 2022). Recent studies have increasingly incorporated microscale factors (for example, street quality, traffic flow, and physical environment) and subjective-level criteria (for example, safety, comfort, and pleasantness) into walkability evaluations (Blecic, Cecchini & Trunfio, 2018; Howell *et al*., 2019; Bivina & Parida, 2019; Hooi & Pojani, 2020; Labdaoui *et al*., 2021; Li *et al*., 2023).

Previous approaches have not mathematically evaluated optimal design criteria, which complicates reaching a consensus on walkability and designing truly walkable streets. This gap prevents a comprehensive understanding of the subjective and multidimensional aspects of walkability, thereby hindering the establishment and application of objective criteria in the design process.

For the effective implementation of these concepts, it is crucial to first identify the areas that require improvement in terms of walkability. In addition, the absence of a universally accepted framework for setting standards on walkability-related variables further complicates the process. As a result, there is a lack of a formally integrated assessment and development framework for walkability within urban planning and design processes. This shows the necessity of developing a new strategy to address these issues. In previous studies in this area, urban design qualities (imageability, legibility, enclosure, human scale, transparency, connectivity, complexity) (Ewing & Handy, 2009) or built environment features (sidewalk width, street width, tree canopy, building height, quality of route) (Southworth, 2005; Ewing & Handy, 2009) were mentioned to improve walkability. However, no study has revealed the optimum design criteria, by mathematically evaluating the built environment variables related to walkability. In this study, for the first time, design-multivariate optimisation procedures were proposed to reveal optimal design criteria associated with walkability.

This study aims to increase the quality of life of society, by contributing to the improvement of walkability in urban design. Therefore, the study uses approaches including network analysis and a multivariate optimisation to develop optimal design criteria for pedestrian routes. In the first stage of the research, walkability was evaluated throughout the study area. The walkability levels at high, medium, and low magnitudes were determined by the spatial network analysis, and then, the low level was defined as pedestrian routes needing development in terms of walkability. In the second stage, a design-multivariate optimisation approach was applied to mathematically provide the correct design, by enhancing the walkability factors. In this stage, 20 streets were analysed, and corresponding data were arranged as a design matrix. The responses for this design matrix were obtained from the expert questionnaire. A multivariate optimisation procedure using a second-order quadratic function obtained from the relationship between the design matrix (independent variable) and corresponding expertise responses (dependent variables) was used to provide the optimal design criteria of walkability. The data obtained from mathematical computations provided a new perspective and alternative opportunity for solving the complex structure of the correct design. Consequently, the results of this article would provide a simple and suitable approach to generating the right solution, in order to make cities more walkable using techniques such as spatial network analysis and design-multivariate optimisation procedures in future work.

2. LITERATURE REVIEW: URBAN DESIGN AND WALKABILITY

The concept of ‘urban design’, which emerged in the mid-1950s, has been rarely mentioned for 20 years (Lang, 2017). However, at present, understanding the impact of urban design on society’s quality of life has become an important concept researched by many disciplines. Urban design combines many elements of space creation, environmental responsibility, social equity, and economic viability (Yeang, 2000). It expresses the relationship between different structures such as parks, waterways, squares, buildings, streets, and other areas that make up public space (DoE, 1997). It is important for urban development that urban design is technically and artistically advanced. Sitte’s main concern was the artistic design and decoration of streets and squares, and thus he is described as the founder of urban design (Moughtin, 2003). Sitte’s pioneering work has elaborated on the design achievements of the past and has thus gathered the principles that contributed to the quality of his compositions (Sitte, 1945). In the early 1960s, urban design studies focused on the perception of the built environment. Important examples of these works are Gordon Cullen’s *Townscape* and Kevin Lynch’s *The image of the city*. Cullen (1968) introduces the concept of serial vision, a key aspect of his work, which examines the sequential experience of urban space. Through detailed perspective

sketches, he systematically analyses the spatial composition, capturing how urban forms unfold dynamically as the viewer moves through the environment.

Lynch (1960) focused on the forms, colours, and textures of the city through drawings and mental maps. As a result, Lynch (1960) formulated his concept of 'Imaginability' (the elements of urban structure that must be present to create a strong visual image in the eye or mind of the beholder). Bentley *et al*. (1985) emphasised that design influences choice in their research on urban spaces. According to Bentley *et al*. (1985), design affects people's destination, the place to use, perception of opportunities, the purpose of use, sensory experiences, and personalisation of a place. They call it creating responsive environments to the vision that the built environment should provide a democratic environment by enriching users' opportunities, by maximising the degree of choice available to them. Addressing the problems of modern design, Jacobs and Appleyard (1987) also presented a set of recommendations necessary for the future of a sustainable urban environment in their *Urban Design Manifesto*. Access to opportunity, imagination, and joy, an environment, and liveability for all are some of them. In short, according to the urban design perspective, there is an important relationship between the opportunities offered by the built environment to the citizens and the way in which people perceive and use these areas.

The concept of walkability similarly focuses on the relationship between the built environment and human mobility. This explanation reveals that there is a strong linear connection between walkability and urban design. Some researchers emphasise the importance of the environment on walking and state the effect of the built environment in facilitating or restricting walking. Park *et al*. (2013) proposed improving the pleasantness, liveliness, safety, and complexity of the pedestrian environment, by associating the design elements of the walking environment with the main perception factors. Ewing and Handy (2009) measured urban design attributes related to walkability. Their studies evaluated the relationship between street environment and walking behaviour, by measuring the street environment. Ewing and Cervero (2010) stated that design is one of the crucial factors affecting walking behaviour. Dong *et al*. (2019) compared the satisfaction of those living in gated and open communities with walkability in their study in China focusing on: "What environmental elements make up a walkable neighborhood?". Gaglione, Gargiulo and Zucaro (2019) conducted a study on optimising pedestrian access to city services, by focusing on physical characteristics (places), functional features (activities), and people's behaviour (lifestyles). According to the researchers, walking primarily occurs on neighbourhood streets and public facilities (Lee & Moudon, 2004), and the character of such places affects the degree to which they are safe, comfortable, and attractive for walking (Saelens & Handy, 2008). In this framework, planning researchers focus on determining the physical-environmental variables related to walking (Alfonzo, 2005). For this reason, researching the concept of walkability, which is an important element in people's lives in terms of social, economic, and health aspects, would enable the production of effective solutions in creating better urban spaces and the development of liveability.

3. STUDY AREA

The integrated strategy for creating walkable cities proposed in this study was implemented in Çankaya district of Ankara Province. The Çankaya district is located in Ankara, the capital of Turkey, and contains

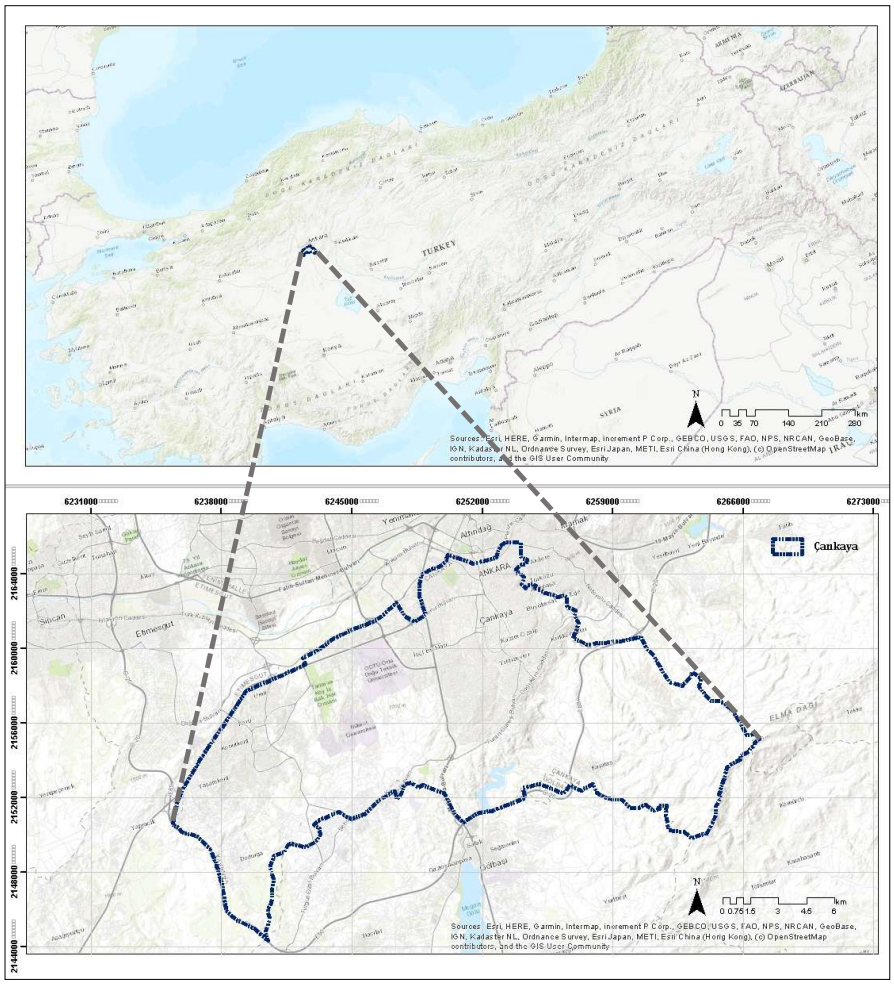

Figure 1: The study area
Source: Authors

historically important cultural centres. Nowadays, it hosts important commercial and state institutions, as well as residential settlements. This district has been determined as the study area (Figure 1).

Çankaya is located in the central Anatolia region of Turkey. The district's total area is 1,157km^2 (Çankaya, 2021). It is the second most populous district with a population of 925,823 in Ankara (ABPRS, 2020). It lies at roughly 870 meters above sea level, and includes 117 neighbourhoods. There are 12 universities and 114 embassies in the district (Design, 2021). In this region with a continental climate, the winter months are cold, and the summer months are hot. The only lake in the district is Eymir Lake. The forest (oak trees) area of the district is located between Elmadağ, Eymir Lake, and Çaldağı and the forest area in the Oran neighbourhood (Çankaya, 2021). In the district, monuments and buildings such as Anıtkabir, Atatürk Museum, Pink Mansion, Zafer Monument, Güvenlik Monument, Güven Park, and the Turkish Grand National Assembly are among the works that tell the recent history of Turkey. Other tourist attraction centres of the district include the Natural History Museum, the Ethnography Museum, the Middle East Technical University Archaeology Museum, the Painting and Sculpture Museum, Anıt Park, Botanical Garden, Abdi İpekçi Park, Kurtuluş Park, Milli Güvenlik Park, the Toy Museum, the Hatti Monument, and Atakule (Çankaya, 2021) (Figure 2).

Transportation in Ankara, which was a small settlement around the castle in the 1920s, was based on pedestrian mobility, due to the topography. With the establishment of the Republic, a limited number of automobiles were included in transportation. As the 1930s approached, the city began to spread with a rapidly increasing population (Tekeli, 2010). In 1958, 42 bus lines with a length of 273km were in service in Ankara. In this process, while the General Directorate of Electric Gas Bus (EGB) buses serve the newly developing areas of the city, small entrepreneurs serve in the central areas where the travel demand is high, and the public share in vehicle transportation has fallen below 50%. The supply provided by EGB was insufficient, especially in the city centre, and this situation caused the emergence of new small entrepreneurship types in the centre. During this period, transportation by minibus, a new vehicle that carried 11 passengers, started to develop. In the 1970s, within the framework of the developments in transportation planning in Turkey, transportation plans that formed the basis of Ankara's first subway were put forward in 1985 (Tekeli, 2010). The first metro line in Ankara was opened in 1996. At present, there are 22 metro stops belonging to three different lines.

From the past to the present, transportation systems have changed as far as planning and population are concerned. Transportation in the Çankaya district is largely based on private vehicles and bus transportation, in parallel with the development of highways. Nowadays, there are two bus stations and 382 bus stops in Çankaya district (Figure 3).

This area is a densely populated urban zone characterised by mixed-use development, resulting in a high number of street users. In this context, assessing walkability and improving urban living standards in response to the challenges



Figure 2: The built environments of Çankaya
Source: Authors

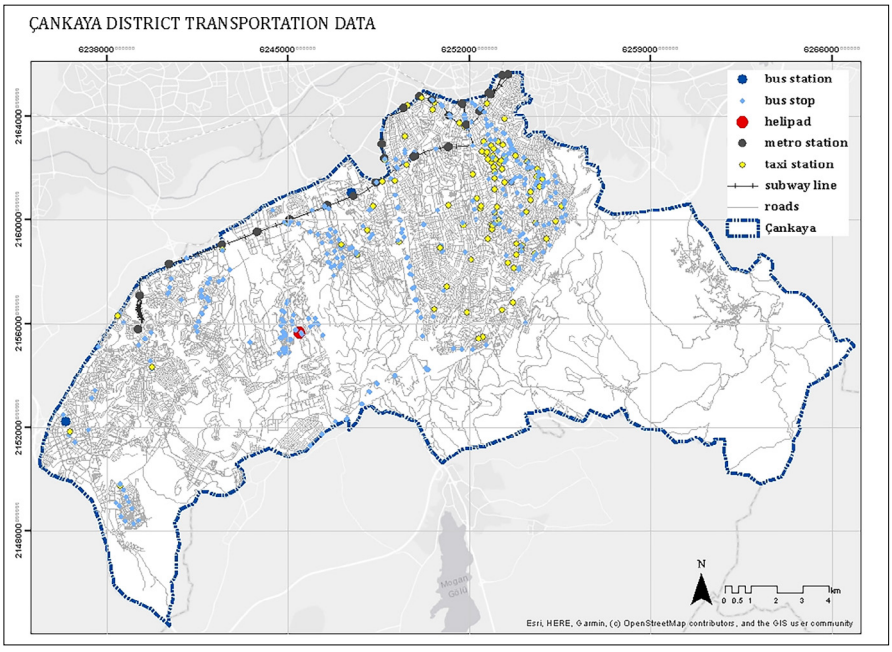

Figure 3: Çankaya district transportation data map
Source: Authors

posed by intense and complex urban processes presents a significant opportunity. Furthermore, enhancing the walkability of streets in Turkey requires strengthening the decision-support processes of local governments through scientific research (Dinç & Gök, 2024). In this regard, integrating evidence-based analyses and academic studies into policymaking processes for defining and implementing walkability criteria may contribute to the adoption of sustainable and human-centred urban design approaches.

4. METHODOLOGY

4.1 Research design

This study used quantitative research to propose an integrated strategy for creating walkable cities (Young & Ewing, 2020). The framework proposed evaluates walkability as a function of multiple spatial and design variables in urban areas, applying both GIS-based network analysis and optimisation procedures. Both qualitative and quantitative variables were considered in the evaluation, ensuring a holistic understanding of urban walkability (Young & Ewing, 2020). In the evaluation process, qualitative and quantitative variables related to urban layout and design were identified through an extensive review of the walkability-related literature (Lee & Moudon, 2004; Southworth, 2005; Ewing & Cervero, 2010; and so on). For evaluation of walkability, in the first stage, the spatial variables for the entire street network of the Çankaya district were assessed, using network analysis techniques in GIS to compile a map of walkability levels (Rock & Malhoski, 2018). This analysis identified the pedestrian routes that require improvement in terms of walkability. In the second stage, the same spatial variables were applied to analyse 20 streets, and the data were presented as a design matrix to experts for ranking. The expert responses were set as the dependent variables. The variables were subjected to multivariate regression analysis to observe the relationship between the design matrix (independent variable) and the corresponding expert responses (dependent variables). This analysis showed how the responses are influenced by the factors in the matrix, which can determine the optimal values for the factors to achieve the best outcomes (Ferreira *et al*., 2019). The results from this multivariate optimisation analysis were used to provide both the optimal design criteria of walkability in urban design and planning and spatial suggestions for improving walkability on streets (Mosey & Deal, 2020).

4.2 Sample composition and expert response in optimisation analysis

The study focused on the streets of the Çankaya district, a dense urban area in Turkey. A total of 20 streets were selected as the sample for optimisation analysis. The sample size was determined based on statistical considerations, ensuring that 20 streets would provide reliable and meaningful results for the multivariate optimisation procedure (Li, Xu, Wei & Wang, 2022).

To support the optimisation analysis with expert evaluation, a total of 50 professionals from urban planning-related disciplines were engaged. Participants were professionals from landscape architecture (22), urban planning/ engineering (13), architecture (12), and civil engineering (3), holding doctoral (26), master's (17), or bachelor's (7) degrees. All participants were selected through purposive sampling, based on their expertise in areas such as pedestrian experience, spatial design, and urban planning, and they all fully completed the evaluation forms. Purposive (or expert) sampling is widely used in content validity and scale development studies, where the goal is to obtain informed judgements from individuals with specialised knowledge in the field. In line with these methodological norms, the selected sample of 50 experts is considered both sufficient and appropriate for ensuring the content validity of the evaluation instruments and supporting the robustness of the optimisation analysis (Krejcie & Morgan, 1970).

4.3 Data collection

First, the spatial variables were determined, by conducting a literature search (Lee & Moudon 2004; Southworth, 2005; Alfonzo, 2005; Saelens & Handy, 2008; Ewin & Handy, 2009; Ewing and Cervero 2010; Park *et al*., 2013; Sevtsuk, Kalvo & Ekmekci, 2016; Du, Mak &Tang, 2018; Dong *et al*., 2019; Gaglione *et al.*, 2019). Secondly, data collection for network analysis and optimisation analysis was initiated. The data-collection phase involved separate processes for network analysis and optimisation analysis, as the spatial variables were evaluated on different scales in each process.

For the network analysis, the Çankaya street network data was obtained from open-access databases such as Open Street Map, Google Maps, Copernicus, and the zoning plan from Çankaya municipality. In addition, the zoning plan of Çankaya, provided by the municipality, was used for a detailed understanding of the area's layout.

For the optimisation analysis, data on both qualitative and quantitative spatial variables were gathered through fieldwork and street photographs. The qualitative data focused on aspects such as the surface condition, the condition of sidewalks, barriers on the sidewalk, and the overall environmental quality. These factors were coded and categorised to provide a structured dataset. A binary coding system was employed to convert qualitative features into numerical variables and to standardise the data. In this system, a value of '1' generally represents a condition considered positive in terms of pedestrian comfort or walkability, whereas a value of '0' indicates a negative or less favourable condition. The quantitative data focused on the presence of trees, road width, sidewalk width, and so on.

Expert feedback collected through a questionnaire survey allowed for the identification of the dependent variables (responses) used in the optimisation analysis. The survey form consists of two sections. Section one included five

demographic questions to gather information about the participants' demographic and professional profiles. Section 2 included 20 street photos selected from the study area for visual assessment. Representative street photographs, capturing both the overall street layout and pavement characteristics, were included in Section 2 (see Figure 4). Experts assessed the selected streets and evaluated them by scoring factors such as comfort, safety, and aesthetics on a scale from 1 to 10, where 1, represents the lowest quality, and 10, represents the highest quality. All 50 experts who participated in the survey answered all questions completely, providing a full dataset for content validity assessment and optimisation analyses.

4.4 Data analysis

The collected data were analysed, using a combination of network analysis and multivariate optimisation techniques, both of which are quantitative methods commonly employed in spatial and urban studies (Newman, 2018; Hair *et al*., 2019).

4.4.1 Network analysis

For network analysis, ArcGIS software was used to determine the walkability levels of each street segment (Rock & Malhoski, 2018). These levels were based on a set of predefined thresholds (limits) for each spatial variable (for example, road width, sidewalk width, building heights, and so on). The criteria for determining the limit values used in the network analysis were established based on a review of relevant literature described below (see Table 1). Six quantitative and 11 qualitative variables were considered for network analysis (Table 1). The analysis identified areas with low walkability scores, which were subsequently targeted for improvement.

According to Turkey's Municipal Building and Roads Law (No. 2290) (1933), the minimum and maximum road widths are set at 4.5 meters and 14.5 meters, respectively. Given this range, an average value of 9.5 meters was selected as the limit for road width. This decision is justified by the relationship between road width and traffic speed. Wider roads tend to encourage higher vehicle speeds, which can negatively impact pedestrian safety and comfort. Increased traffic speeds contribute to environmental disturbances, including higher exposure to exhaust emissions, which pose health risks to pedestrians.

Sidewalk dimensions were determined following the guidelines provided in the *Urban Roads – Design Criteria for Preventive Barriers on Sidewalks* (TSI, 2017). This handbook specifies a minimum sidewalk width of 1.5 meters to ensure optimal pedestrian mobility. Furthermore, sidewalks should be free from obstructions such as flower beds, stones, poles, traffic signposts, notice boards, and trees that could hinder pedestrian movement.

The handbook also recommends that sidewalks be paved with easily removable and reusable materials such as cobblestone or concrete paving blocks, to facilitate maintenance and repairs.

Slope conditions also play a crucial role in pedestrian accessibility. The Chamber of Architects of Turkey suggests a maximum slope of 8% to accommodate individuals with varying mobility needs (Olguntürk, 2007). In addition, prior studies have highlighted the influence of building heights on pedestrian experience and urban spatial definition. Research by Du *et al.* (2018) indicates that taller buildings contribute to increased wind speeds, potentially affecting pedestrian comfort. A study in Dresden, Germany, further demonstrated that urban spaces, defined by four- to six-storey buildings, along with focal sculptures



Figure 4: Street photos used in the survey
Source: Authors

Table 1: Quantitative and qualitative variables for network analysis

Quantitative variables	Limits	
Road width	≤9.5m=1	>9.5m=0
Sidewalk width	≤1.5m=1	>1.5=0
Building heights	≤24m=1	>24=0
Connectivity with other modes	≤15min=1	>15min=0
Block size	≤8192m2=1	>8192m2=0
Slope	≤8%=1	>8%=0
Qualitative variables	**Limits**	
Buffer type	1=tree, other	0=no
Flooring type	1=stone covering, stone pavement	0=asphalt
Surface condition	1=good, moderate	0=poor
Environmental status	1=natural area, green area	0=no
Barriers on the sidewalk	1=no	0=yes
Aesthetic appearance	1=good, moderate	0=poor
Sidewalk height	1=good	0=poor
Parked vehicles	1=yes	0=no
Plants	1=yes	0=no
Cul de sac	1=no	0=yes
Lighting density	1=good	0=poor

and traditional street elements, were preferred by pedestrians over modernist environments dominated by high-rise structures (Southworth, 2005). Based on these findings, the building height limit in this study was set at six floors, with a maximum floor height of 4 meters.

Block size also influences pedestrian accessibility and route efficiency. Large block sizes and cul-de-sacs tend to extend walking distances, reducing connectivity. According to research by Sevtsuk et al. (2016), block widths of 64 to 128 meters optimise pedestrian accessibility within a 15-minute walk. These dimensions support a mix of residential and commercial uses, while maintaining walkable urban environments. Pedestrian accessibility is further enhanced when three parcels are allocated per street frontage, allowing for diverse land-use configurations.

Beyond physical design, walkability also depends on effective integration with public transportation networks. Southworth (2005) emphasises that a well-connected pedestrian network should be complemented by efficient links to public transit, including bus, tram, subway, and train services. Ideally, transit stations should be located within a 10- to 20-minute walking distance from residential and commercial areas, in order to maximise accessibility. Southworth (2005) also identifies several key indicators of a walkable city, including road width, pavement type, path context, signage, lighting, street design, visual interest, spatial definition, landscape elements, and overall usability.

4.4.2 Multivariate optimisation analysis

Multivariate optimisation analysis is widely applied across various disciplines, including food science (Ferreira *et al.*, 2019), ecological studies on the spread of grass, and financial portfolio optimisation (Al Janabi, 2020). In addition, Mosey and Deal (2020) used multivariate optimisation to develop an architectural and urban design approach that balances social, environmental, and economic sustainability in large-scale construction projects. However, this study represents the first application of multivariate optimisation analysis to establish optimal design criteria for improving walkability.

Optimisation methods are increasingly preferred, due to their ability to reduce the number of preliminary studies and data-collection processes required while improving the efficiency of analysis. These methods enable the development of mathematical models that assess both the statistical significance and the relevance of factors influencing outcomes (Wright, 2022). In addition, optimisation allows for the evaluation of interaction effects between variables, providing a more comprehensive understanding of complex relationships.

In multivariate optimisation, two main types of variables are considered: responses and factors. Responses (also referred to as dependent variables) are influenced by the factors, which can be either qualitative (for example, material types, environmental conditions) or quantitative (for example, road width, sidewalk height). If the nature of the relationship between responses and factors – referred to as the response surface – is well understood, optimal factor values can be determined (Ferreira *et al.*, 2019). In this study, six quantitative and six qualitative spatial variables were considered in the optimisation analysis (Table 2).

Before conducting the optimisation analysis, data scaling was applied to mitigate overfitting in mathematical modelling. Due to variations in the properties of quantitative variables across different data columns, a standardisation process was implemented to ensure consistency in data range and variance. The range scaling of the data was performed by the equation (1).

$$x_{ik}^{*}=\frac{x_{ik}-x_k(min)}{x_{ik}(max)-x_k(min)} \qquad 0 \le x_{ik}^{*} \le 1 \qquad (1)$$

Where i the row is the index, and k denotes the column index. Due to the different properties of the quantitative variables data changing from column to column, a standardisation was realised, by scaling our data to similar ranges and variances. The relationship between independent and dependent variables was then modelled, using multivariate regression analysis. The relationships between independent variables (for example, road width, sidewalk height) and dependent variables (expert evaluations of walkability) were modelled, using a second-order quadratic function. The optimisation function was formulated as a second-order quadratic model, where:

$$y = \beta_0 + \sum_{i=1}^{k} \beta_i x_i + \sum_{i=1}^{k} \beta_{ii} x_i^{\,2} + \sum_{i\ge j}^{k} \sum_{i=1}^{k} \beta_{ij} x_i x_j \qquad (2)$$

In equation (2), x_i and x_j are the independent factor variables, y denotes the dependent output or the predicted response; k represents

Table 2: Quantitative and qualitative variables were collected by fieldwork for optimisation analysis

Quantitative variables			
Road width (cm)			
Sidewalk width (cm)			
Sidewalk height (cm)			
Number of parked vehicles			
Number of trees			
Building heights (m)			
Qualitative variables	Codes		
Buffer type	0=other	1=tree	-1=no
Flooring type	0=stone pavement	1=stone covering	-1=asphalt
Surface condition	0=good	1=moderate	-1=poor
Environmental status	0=green area	1= natural area	-1=buildings
Barriers on the sidewalk	0=good	1=moderate	-1=poor
Aesthetic appearance	0=good	1=moderate	-1=poor

the number of variables (factors); β_0 is called the intercept; β_i and β_{ii} are called the coefficients of the linear effect and squared effect in the model, respectively; β_{ij} the coefficient of the interaction effects of factors, where $i = 1,2, \ldots, k$ and $j = 1, 2, \ldots k$. Hence, from equation (2), the optimal experimental parameters can be obtained. To find optimal values for the model equation, the derivation or differential of the second-order equation should be taken. Optimal walkability conditions were computed from the mathematical solution of the obtained modelling function. This mathematical model provided insights into how different design features interacted and which combinations of these features would lead to optimal walkability conditions.

5. RESULTS AND DISCUSSION

In this study, an integrated strategy for creating walkable cities that combines optimisation and network analysis is proposed to make cities more walkable. This study's proposed strategy consists of two fundamental steps. The first step involved a district-wide assessment of walkability in Çankaya, using network analysis, a widely recognised method in urban studies (Lee & Moudon, 2004; Park *et al.*, 2013; Sevtsuk *et al.*, 2016; Du *et al.*, 2018; Dong *et al.*, 2019; Gaglione *et al.*, 2019). Traditionally, network analysis focuses on large-scale quantitative variables such as road width, block size, and slope. However, this study also incorporated qualitative and microscale variables, such as aesthetic appeal and flooring type, to provide a more comprehensive evaluation of pedestrian perception. The second step applied optimisation analysis to determine optimal urban design standards by integrating both qualitative and quantitative microscale data. This optimisation model represents the first mathematical model applied in this field for the optimisation of walkability. Mathematically defining walkability design criteria offers a valuable decision-support tool for policymakers and urban planners.

5.1 Results of the network analysis

The results of the analyses provide critical insights into pedestrian routes. The network analysis used the variables outlined in Table 1 and classified streets into three walkability levels (see Figure 5). In Figure 5, blue roads indicate high-walkability streets, while grey roads represent those with low walkability. Notably, high to medium walkability routes (blue and orange roads) are concentrated in certain areas, yet their connectivity is limited, highlighting the need for improved pedestrian connectivity between them.

Considering the walkability variables, the analysis indicates that the south-east section (grey roads) of the study area lacks sufficient connectivity to other regions, primarily due to inadequate public transportation infrastructure. Metro and public transport systems play a crucial role in supporting pedestrian mobility. However, Çankaya has only 22 metro stations, a number that is insufficient, given its urban density. For comparison, Los Angeles, with a population of approximately 4 million, has 93 subway stations (Juliano, 2024). In contrast, Ankara, with nearly 6 million residents, has only 53 stations (ABPRS, 2020). European cities, which generally offer higher walkability, have significantly more stations. London, for example, has 270 stations for a population of 8 million (LRSL, 2025), while Amsterdam, with only 820,000 residents, has 52 stations (Wikimedia Commons, 2025). In addition, European cities supplement their public transit with extensive bicycle networks. In Çankaya, metro stations are primarily located in the northern and western parts of the district, while the eastern section lacks any public transport hubs. To enhance walkability in low-scoring (grey) areas, the pedestrian network must be integrated with public transport through strategically placed stops and railway stations within a 10-15-minute walking distance.

High-walkability areas in central Çankaya are largely shaped by early urban planning principles. Following the approval of the Jansen Plan in 1923, neighbourhoods were developed using the Garden City approach, characterised by two- to three-storey buildings with gardens and pedestrian-friendly block sizes. However, the enactment of the Property Ownership Law (1965) led to increased building heights and expanded structures, reducing garden spaces. Despite

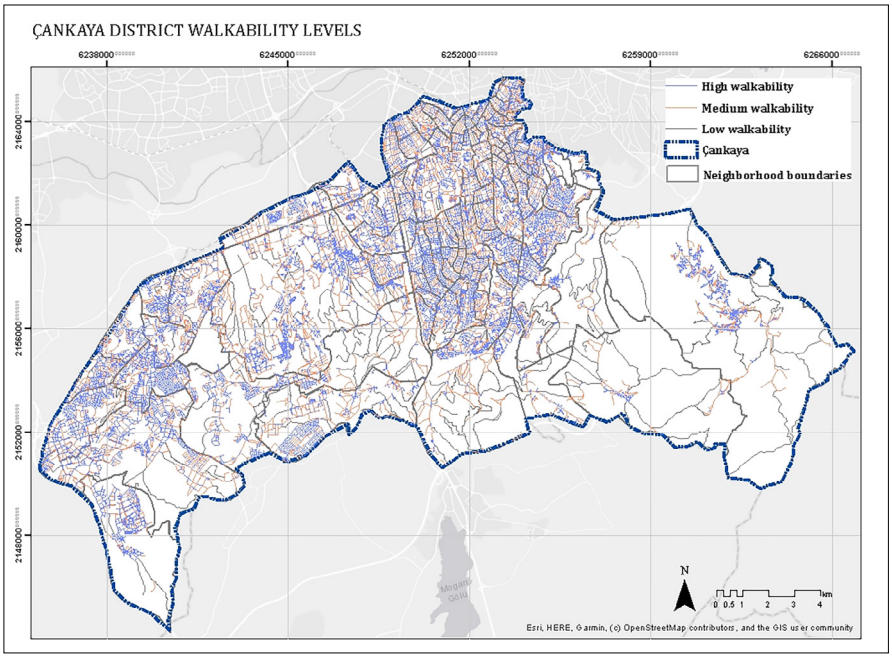

Figure 5: Results of the network analysis

Source: Authors

these changes, many areas still maintain human-scale urban forms with five- to six-storey buildings, promoting walkability. One example is Bahçelievler, a neighbourhood in north-central Çankaya, which exhibits high walkability values (Figure 6).

Other neighbourhoods with high walkability include Yaşamkent, Koru, Çayyolu, Ümit, and Prof. Dr. Ahmet Taner Kışlalı. In contrast, Mutlukent, Alacaatlı, Üniversiteliler, and Ahlatlıbel have moderate walkability but contain pockets of low-walkability zones, due to large block sizes and insufficient public transport.

A specific example is 2526th Street in the Ümit neighbourhood (Figure 7). This street meets many walkability criteria, including appropriate building heights, block sizes, and multimodal transportation connections. It is within a 10-minute walk of both metro and bus stops, which significantly enhances its accessibility. The street is also lined with low-rise houses and trees and has a road width of 8 meters, contributing to a pedestrian-friendly atmosphere. However, the sidewalk width and height are inadequate for pedestrian mobility. According to expert evaluations, this street received the lowest walkability score in the optimisation analysis. As Alfonzo (2005) suggests in the hierarchy of walking needs, feasibility is a fundamental factor influencing pedestrian perception. Experts rated the street poorly. due to its narrow sidewalk, which makes walking difficult. However, at the broader planning scale, a walkability analysis indicated that the street had a high walkability level. The experts' low rating of 2526th Street shows the need to incorporate human perception and prioritise spatial factors based on their importance for walkability in urban design analyses.

Implications for urban planning. Although the central and western neighbourhoods of Çankaya generally exhibit medium to high walkability, specific streets and avenues require targeted improvements in terms of walkability. One major issue is oversized block sizes, which exceed optimal walkability thresholds (limits). New urbanism principles such as infill development and street hierarchy design could reduce block sizes and create a more pedestrian-friendly urban fabric.

The eastern section of the district consistently demonstrates low walkability. To address this, planners must integrate pedestrian-focused urban design with improved public transport, particularly rail-based systems. Increasing the number of metro stations and ensuring seamless connectivity with pedestrian networks will significantly enhance walkability in these underserved areas.

Network analysis proved to be an effective tool for evaluating key urban variables such as block sizes, slope, cul-de-sacs, and connectivity with transportation networks. However, optimisation analysis provided additional insights, by determining the most suitable design criteria for pedestrian-friendly streets.

5.2 Results of the multivariate optimisation analysis

Based on the analysis of 20 street photographs, the optimal urban street design criteria for enhancing walkability were established. Table 3 presents the spatial data



Figure 6: Bahçelievler neighbourhood plan view
Source: Authors



Figure 7: 2526th Street
Source: Authors

Table 3: Spatial data and response factors derived from the expert survey results

Street name	Spatial data												Total score
	Road width (cm)	Sidewalk width (cm)	Sidewalk height (cm)	Number of parked vehicles	Number of trees	Building heights (m)	Buffer type	Flooring type	Surface condition	Environmental status	Barriers on sidewalk	Aesthetic appearance	
1938	670	192	9	0	8	3	1	-1	1	-1	-1	1	311
2435	1500	225	9	15	14	5	-1	0	0	-1	0	1	263
2450	760	390	19	1	16	3	1	-1	0	1	0	0	360
2482	530	103	9	0	6	3	1	1	-1	1	-1	-1	241
2502	780	125	18	1	6	5	-1	0	0	0	-1	0	215
2505	600	190	13	5	7	3	0	0	1	0	1	1	207
2506	604	180	13	3	6	2	1	0	0	-1	1	-1	309
2511	530	170	9	4	10	4	-1	0	1	-1	-1	-1	283
2512	660	97	10	6	0	3	-1	0	-1	0	-1	-1	261
2526	670	140	6	3	3	3	-1	1	0	-1	1	1	143
2539	600	200	9	5	5	9	0	0	0	-1	1	-1	166
Attar	610	210	19	7	8	3	1	-1	1	-1	-1	-1	287
Billur	360	100	24	0	1	5	0	1	-1	-1	-1	-1	284
Binnaz	610	160	15	9	5	4	1	-1	0	-1	-1	-1	154
Boğaz	600	170	5	8	6	4	0	-1	1	-1	-1	1	190
Borazan	380	230	1	1	0	6	0	1	0	-1	0	-1	223
Çığı	580	390	3	10	9	4	0	-1	0	-1	0	-1	237
Güniz	545	105	5	4	5	4	0	1	1	-1	-1	-1	274
Haliç	600	150	4	6	9	5	0	-1	0	0	1	0	208
Omerhaluk	550	190	11	4	7	3	1	0	0	-1	0	1	232

collected from field studies and the results of the expert survey, which informed the response factor in the optimisation analysis. Table 3 provides total scores from expert evaluations for 20 streets, as well as key spatial variables such as aesthetic appearance, sidewalk barriers, environmental conditions, surface conditions, flooring type, buffer type, building heights, number of trees, number of parked vehicles, sidewalk height and width, as well as road width. These factors were assessed to determine their impact on pedestrian experience and walkability.

Table 4: Optimal values for street design derived from the optimisation analysis

Variables	optimum values
Road width (cm)	520
Sidewalk width (cm)	150
Sidewalk height (cm)	8,5
Number of parked vehicles	11
Number of trees	5
Building heights (m)	19
Buffer type	tree
Flooring type	stone pavement
Surface condition	moderate
Environmental status	buildings
Barriers on sidewalk	good
Aesthetic appearance	good

Calculations were made on how different design features interacted and which combinations of these features would lead to optimal walkability conditions. Table 4 presents the optimal pedestrian preferences for walkability in the streets.

Findings indicate that sidewalk width should increase on wider roads to balance pedestrian and vehicular traffic. The optimal sidewalk width on a street with a 5-meter road width was determined to be 1.5 meters. Excessively wide roads encourage higher traffic speeds, creating an unfavourable environment for pedestrians. By limiting road widths and distributing traffic across multiple streets, cities can enhance pedestrian accessibility and promote human-scale urban design. Sidewalks should be designed to accommodate foot traffic comfortably (Ewing, 1999), while maintaining a balance between liveliness and spaciousness.

Regarding sidewalk height, the *Urban roads – Structural preventive and sign design criteria on accessibility in sidewalks and pedestrian crossings* handbook by TSE sets a maximum sidewalk height of 15 cm. This study found 8.5 cm to be optimal for urban roads and residential areas. Reducing sidewalk height and implementing appropriate ramp systems ensures accessibility for all residents. Many European cities use distinct

pavement types instead of raised sidewalks to separate pedestrian and vehicular areas, slowing down the traffic and enhancing safety, while creating barrier-free walkways.

Building heights also influence pedestrian perception. The analysis determined that, for streets with road widths of 5-6 meters, an optimal building height of 19 meters provides a sense of enclosure, aiding in spatial definition. Higher buildings help frame the street, improving orientation and pedestrian comfort. However, as noted by Du *et al*. (2018), increasing building heights can raise wind speeds, potentially creating discomfort for pedestrians. At the same time, taller buildings encourage drivers to reduce speed, making streets more pedestrian-friendly (Smith & Appleyard, 1981; Ewing, 1999). When street width increases beyond a certain point, trees become essential to maintaining a sense of enclosure. Thus, spatial definition is achieved through focal points rather than enclosures. The visual coherence between building facades and the street is as crucial as building height for aesthetic integrity. Prominent landmarks, street-facing entrances, and ample windows at street level enhance spatial definition, security, and transparency (Jacobs & Appleyard, 1987).

Regarding street flooring, stone pavement emerged as the preferred material. In Çankaya district, asphalt pavements are commonly used but are less favoured, due to difficulties in infrastructure maintenance, poor drainage during rain causes water accumulation on the sidewalk and reduced pedestrian comfort. Sidewalk surfaces should be non-slip and appropriate for local climatic conditions to ensure safety during wet or icy weather.

The presence of buildings surrounding streets was found to be optimal for pedestrian comfort. Buildings provide physical boundaries, enhancing safety, defining the street space, and offering a sense of direction. They also contribute to the overall aesthetic and functional coherence of the urban environment.

The study also found that sidewalk surface conditions are not a primary concern for pedestrians, unless they significantly impede walking. However, deteriorated sidewalks physically hinder mobility. Regular maintenance and the use of durable materials are essential to creating long-term pedestrian-friendly environments. The relationship between tree placement and sidewalk surfaces should be carefully managed, in order to prevent damage from roots. A designated buffer zone for vegetation, where feasible, can help mitigate these issues. Tree species should be selected in coordination with traffic considerations, providing pedestrian shade without obstructing drivers' visibility. Expert-established standards should guide implementation to ensure safety and effectiveness.

A good level of barrier presence on sidewalks was identified as an optimal feature. Properly planned buffer zones that separate pedestrians from traffic with elements such as trees, street furniture, and lighting enhance safety and comfort. Aesthetic appeal is another key factor in walkability. Visually interesting elements such as public art, parks, cafes, and distinctive architecture contribute to an engaging pedestrian experience (Dinç & Gül, 2018; Southworth, 2005).

While the optimisation analysis could not determine the exact ideal numbers of trees or parked vehicles per street, it confirmed that pedestrians prefer streets with trees and parked vehicles. Parked cars act as a buffer, enhancing pedestrian safety, by separating walkways from traffic. Trees contribute to human-scale urban design (Ewing & Handy, 2009), provide shade, and enhance street definition (Jacobs & Appleyard, 1987). The importance of trees in walkability is well documented (Stamps, 1997; Landis *et al.*, 2001; Southworth, 2005; Ewing & Handy, 2009).

Security is another fundamental aspect of pedestrian-friendly streets. Landis *et al.* (2001) emphasise that pedestrian networks must be designed to protect against collisions and other threats. This study confirms that buffer zones between pedestrians and traffic enhance safety, with trees serving as an effective buffer type. Alternative solutions such as urban design elements incorporating a mix of trees, bushes, and ground covers can further separate pedestrian and vehicular zones. Parked vehicles also provide protection against high-speed traffic.

Finally, as the analysis was conducted based on photographs taken during the daytime, lighting-related safety factors could not be assessed. Future studies should consider nighttime conditions to provide comprehensive walkability evaluations.

6. CONCLUSION

Creating walkable cities through traditional planning and design approaches presents significant challenges, particularly in Turkey, where resistance to pedestrian-friendly environments persists, due to historically car-oriented urban development. This study aimed to support decision makers, by identifying optimal walkability criteria from an urban design perspective, employing network analysis and optimisation techniques. Network analysis enables the evaluation of urban walkability, by processing multiple spatial components, while multivariate optimisation analysis identifies optimal design values for pedestrian pathways. These methodologies identified streets requiring improvement and determined appropriate design standards. The results contribute to a structured framework for urban planning and walkability enhancement. To validate the proposed framework, the obtained results were compared with existing literature and similar studies. By integrating quantitative and qualitative assessments, the study presents a robust methodological approach that offers data-driven insights for urban design and policymaking.

Investments in street design, proactive planning processes, political support, and tactical urban interventions can enhance urban quality of life and spatial justice (Carmona, 2021; Tsoriyo *et al*., 2021). Research indicates that service levels, land-use diversity, density, and street atmosphere influence pedestrian safety and comfort. Poor street design that fails to ensure accessibility and comfort often compels pedestrians to use vehicle lanes, posing safety risks. Moreover, inadequate pedestrian infrastructure discourages public transportation use, which depends on walkable access (Ryan & Frank, 2009; Corazza, Di Mascio & Moretti, 2016; D'Orso, 2020; Anapakula & Eranki, 2021). Thus, creating a safe and accessible pedestrian environment is essential for sustainable transportation policies.

Globally, cities have implemented various pedestrian-focused interventions. Artistic pavements, LED-lit virtual stops, and pedestrian-priority initiatives have emerged in Europe (Copenhagen, Lisbon). South American cities (Buenos Aires, Bogota) have introduced wide sidewalks, low-speed zones, and bicycle-sharing systems. North American cities (New York, Toronto) have promoted pedestrian-friendly environments through 3D pedestrian crossings and widened sidewalks. In Asia (Dubai, Singapore), innovative solutions such as ventilated and cooled sidewalks, accessibility ramps, and automated parking systems have been developed (Naugain & Singh, 2022).

In Turkey, pedestrian-focused regulations such as TS 12576 and TS 12716 standards introduced in 2017, outline accessibility criteria for sidewalks and pedestrian crossings. However, these standards require updates to align with international best practices and increasing demand for walkable cities. The integrated strategy proposed in this study offers a data-driven approach to optimising pedestrian infrastructure and accessibility, supporting sustainable urban mobility objectives both in Turkey and internationally.

Local governments are encouraged to adopt decision-support tools, expand pedestrian-friendly zones, update sidewalk standards by global best practices, and introduce municipal incentive mechanisms. In addition, standardising urban-scale walkability assessments, integrating Geographic Information Systems (GIS) and optimisation analyses, as well as encouraging awareness among city planners through guidelines and training programmes are critical steps. Strengthening pedestrian pathways connected to public transportation and implementing policies that enhance accessibility around transit stations are key to achieving sustainable mobility. The proposed methodology is adaptable beyond Turkey and serves as a model for walkability assessments in diverse urban contexts.

The findings of this study should be examined within the broader framework of sustainable transportation and spatial justice to inform actionable recommendations for more liveable cities. Decision-makers must prioritise these principles when defining sidewalk standards. Mathematical modelling provides a robust foundation for efficient pedestrian pathway development, contributing to social welfare, by ensuring equitable access to urban amenities and services. This study highlighted the potential of multivariate optimisation in creating more accessible, comfortable, and pedestrian-friendly urban environments.

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