# Modeling Dynamic Walkability to Support Time-Based Route Planning for Older Adults

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**Abstract**

Walkability assessments for elderly pedestrians are often based on static representations of the built environment, overlooking temporal variations that influence walking conditions throughout the day. This study develops a network-based dynamic walkability framework that integrates static infrastructural characteristics with time-dependent environmental factors to capture spatiotemporal variability in pedestrian suitability. The approach combines sidewalk and arcade-based pedestrian networks with dynamic variables, including traffic, air quality index (AQI), temperature, humidity, shade, and lighting, evaluated at two time periods (12:00 and 17:00) across weekdays and weekends in three urban contexts in Tainan, Taiwan: a hospital area, a university campus, and a residential neighborhood. Results indicate clear spatial differences, with hospital and campus areas showing higher baseline walkability than residential areas. Dynamic analysis reveals temporal variation, with improvements ranging from approximately 3–8% in institutional environments to over 10% in residential areas. Segment-level results further show that temporal factors can alter pedestrian suitability, particularly in areas with limited infrastructure. Route-based validation demonstrates that the model generates alternative paths that prioritize safety and environmental comfort over the shortest distance. Compared to Google Maps routes, the proposed approach achieves higher average walkability, with improvements ranging from approximately 5% to over 15%, particularly in residential areas. These findings highlight the limitations of static and shortest-path approaches and emphasize the importance of incorporating temporal dynamics. The proposed framework supports time-sensitive routing and age-friendly urban planning strategies.

## 1. Introduction

Urban mobility and accessibility are fundamental to enhancing the quality of life in cities, with walkability playing a central role in sustainable urban development (Zhang et al., 2020). Walkability is particularly important for older adults, as it supports safe, comfortable, and independent mobility in daily life. Previous research has demonstrated that sidewalk quality, availability, and well-connected street networks significantly encourage pedestrian activity and facilitate access to public transportation systems (Woldeamanuel and Kent, 2016). Although numerous indicators have been developed to evaluate walkability, only a limited number explicitly consider the specific needs of elderly pedestrians, particularly in relation to environmental stressors such as heat exposure and air pollution (Frank et al., 2010). Furthermore, existing frameworks, such as the Walkability Index for Elderly Health (Alves et al., 2020), primarily rely on static datasets that represent fixed physical conditions, without accounting for temporal variations that influence walking environments throughout the day.

Population aging further amplifies the importance of developing age-friendly urban environments that support independent and healthy living. As walking remains the most accessible mode of transport for older adults, the quality of pedestrian infrastructure directly affects physical activity, social participation, and overall well-being (Shigematsu et al., 2009; Yen and Anderson, 2012). However, elderly pedestrians face greater vulnerability to environmental barriers, including uneven surfaces, inadequate lighting, traffic exposure, and insufficient supporting infrastructure, which can significantly reduce both safety and perceived comfort (Oxley et al., 2018; Ståhl et al., 2008). Features such as curb ramps, resting facilities, and shaded pathways are therefore essential components of elderly-friendly pedestrian environments (Rosenberg et al., 2013).

To address these challenges, several studies have proposed elderly-oriented walkability indices that incorporate factors related to safety, accessibility, and physical effort. Among these, the Walkability Index for Elderly Health (WIEH) introduced by Alves et al. (2020) integrates built environment characteristics with physiological considerations such as slope and walking effort. Subsequent applications have demonstrated its effectiveness in evaluating pedestrian environments for older adults (Alves et al., 2021; Bonatto and Alves, 2022). Other approaches, such as Walk Score, focus on accessibility to destinations within a network distance framework, although they often lack sensitivity to elderly-specific constraints (Horak et al., 2022). In Taiwan, localized adaptations of walkability metrics have been developed to reflect regional characteristics and pedestrian behavior (Lai et al., 2019; Chen et al., 2022). Despite these advancements, most existing approaches continue to treat walkability as a static attribute.

In practice, however, walkability is inherently dynamic. Environmental conditions such as temperature, air quality, traffic intensity, and lighting vary throughout the day and can substantially influence walking comfort and safety. These temporal variations are particularly critical for elderly individuals, who are more vulnerable to environmental stressors such as heat exposure and poor air quality (Pan et al, 2024; Wilkes et al., 2024). Recent studies have begun to explore time-dependent walkability, emphasizing the importance of incorporating temporal variability into pedestrian analysis (Carra et al., 2022; Khalil and Mohamed, 2023). Nevertheless, existing approaches remain limited in their integration of dynamic environmental factors with elderly-focused walkability models.

In addition to temporal limitations, many studies rely on aggregated spatial units such as buffers or administrative zones, which can obscure local variations along pedestrian routes. In reality, pedestrian movement occurs along interconnected network segments, where conditions may vary significantly between adjacent links. A network-based perspective enables more precise representation of pedestrian environments and supports route-level analysis, which is essential for realistic modeling of walking behavior.

Moreover, regional context plays a crucial role in shaping walkability. Urban environments in Asian cities often differ substantially from Western contexts due to features such as arcades (covered walkways), mixed traffic conditions, and high-density development patterns (Hsu et al., 2003; Chen et al., 2022). These characteristics necessitate context-specific adaptations of walkability frameworks to ensure accurate representation of local pedestrian experiences.

To address these gaps, this study integrates built environment characteristics as a static baseline with dynamic environmental factors that significantly affect pedestrian conditions. It proposes a network-based dynamic walkability framework that captures both spatial and temporal variability, with a particular focus on elderly health and mobility. The framework is applied to the National Cheng Kung University and its surrounding urban areas in Tainan, Taiwan, encompassing three distinct urban contexts: a hospital area, a university campus, and a residential neighborhood.

The contributions of this study are threefold. First, it extends conventional walkability assessment by incorporating temporal dynamics into an elderly-focused framework. Second, it adopts a network-based approach that enables segment-level evaluation and more realistic representation of pedestrian movement. Third, it provides empirical evidence on how dynamic environmental conditions reshape walkability patterns across different urban contexts, supporting the development of age-friendly and health-oriented urban planning strategies.

The remainder of this paper is organized as follows. Section 2 presents the study area, data sources, and methodological framework. Section 3 reports the results of static and dynamic walkability analyses. Section 4 discusses the implications of the findings and outlines limitations. Finally, Section 5 concludes the study and suggests directions for future research.

# 2. Methods

## 2.1 Study Area

This study was conducted in Tainan City, Taiwan, focusing on three urban contexts surrounding National Cheng Kung University (NCKU): the NCKU Hospital area, the NCKU campus, and the East District residential neighbourhood, as shown in Figure 1. These areas were selected to represent distinct urban functions and pedestrian environments, including public, semi-public, and residential settings. The study area is located in a highly accessible urban zone near the central business district (CBD), major transportation nodes such as the railway station and bus terminals, and key public services, including the hospital. This strategic location ensures diverse pedestrian activity patterns and makes it suitable for analyzing walkability under varying urban and mobility conditions.

The hospital area is characterized by high pedestrian activity associated with healthcare services and transport access, including a significant presence of elderly users. Sidewalks are primarily located along major roads, while internal spaces are dominated by built structures, resulting in limited greenery and reduced pedestrian comfort. The campus, in contrast, offers a more pedestrian-friendly environment, with well-connected pathways, abundant vegetation, and open public spaces that support walking and outdoor activities. The residential neighborhood reflects typical local walking conditions, where sidewalks are often discontinuous, infrastructure is limited, and streets are more vehicle-oriented. These contrasting characteristics provide a suitable basis for comparative analysis of walkability across different urban contexts.

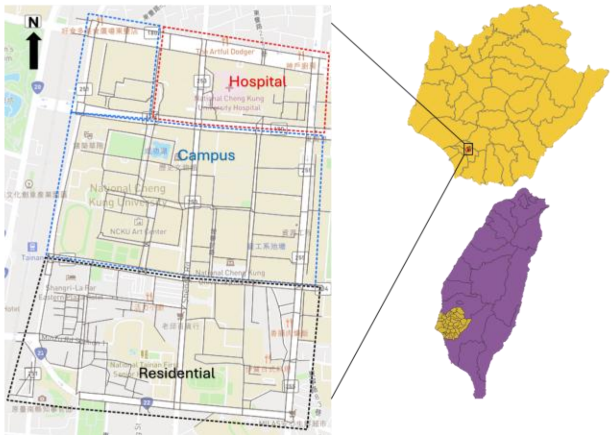


Figure 1. Study area and surrounding urban context, showing hospital, campus, and residential zones.

## 2.2 Data Sources and Preparation

A network-based representation of pedestrian space was developed to reflect actual walking behavior. Sidewalk and arcade datasets obtained from the Tainan City Government were used as the primary sources for modeling pedestrian pathways. Arcades, which are covered walkways integrated into building facades, are a distinctive feature in Taiwanese cities and provide shaded routes that are particularly beneficial for elderly pedestrians. In areas where sidewalk or arcade data were unavailable, road network data from the National Land Surveying Center were incorporated to maintain continuity. Intersection crossings were also included to ensure a fully connected pedestrian network. The final network consists of over 600 connected segments.

Walkability variables were divided into static and dynamic components. Static variables describe physical characteristics of the built environment that remain constant over time, including pedestrian surface quality, sidewalk existence and width, curb ramps, stairs, obstacles, points of interest, vegetation, urban furniture, signage, and CCTV presence, as detailed in Table 1. These variables were adapted from the Walkability Index for Elderly Health (Alves et al., 2020) and modified to reflect local urban conditions. All variables were classified into three levels representing low, moderate, and high suitability, based on field observations, literature references, and local design standards. Slope and stair conditions were incorporated as normalization factors to account for the physical effort required by elderly pedestrians.

<table>
<tr><th rowspan="2">Systematic Areas</th><th rowspan="2" colspan="2">Variables</th><th colspan="3">Weights (%)</th></tr>
<tr><th colspan="2">Partial Weight</th><th>Total Weight</th></tr>
<tr><td rowspan="8">Urban Tissue</td><td colspan="2">Pedestrian surface quality (PSQ)</td><td colspan="2">8</td><td rowspan="8">60</td></tr>
<tr><td rowspan="2">Sidewalk existance and width (SEW) (Average of SE and SW)</td><td>Sidewalk existance (SE)</td><td>6</td><td rowspan="2">12</td></tr>
<tr><td>Sidewalk width (SW)</td><td>6</td></tr>
<tr><td colspan="2">Curb ramp (CR)</td><td colspan="2">12</td></tr>
<tr><td colspan="2">Stairs (EoS)</td><td colspan="2">8</td></tr>
<tr><td colspan="2">Obstacles (EoO)</td><td colspan="2">12</td></tr>
<tr><td colspan="2">Point of Interest (EoP)</td><td colspan="2">8</td></tr>
<tr style="display:none"></tr>
<tr><td rowspan="2">Urban Scene</td><td colspan="2">Trees/vegetation (ETV)</td><td colspan="2">8</td><td rowspan="2">16</td></tr>
<tr><td colspan="2">Urban furniture (EUF)</td><td colspan="2">8</td></tr>
<tr><td rowspan="2">Urban Safety</td><td colspan="2">Diversity of information signs (DIS)</td><td colspan="2">12</td><td rowspan="2">24</td></tr>
<tr><td colspan="2">CCTV</td><td colspan="2">12</td></tr>
</table>

Table 1. The static variable of walkability.

Dynamic variables capture environmental conditions that vary over time and influence pedestrian comfort and safety. These include traffic intensity, air quality index (AQI), temperature, humidity, shade, and lighting conditions. Traffic data were obtained via the Mapbox API, while environmental data such as temperature, humidity, and AQI were sourced from the Taiwan Ministry of Environment. Shade conditions were derived from the ShadeMap API, and lighting conditions were determined based on time-of-day classification supported by field observations.

To ensure spatial consistency, environmental variables were interpolated using Ordinary Kriging. Kriging was selected due to its ability to model spatial autocorrelation and produce continuous environmental surfaces from discrete observations. Semivariogram models were fitted for each variable, and cross-validation was performed to evaluate interpolation accuracy.

Temporal variability was incorporated by focusing on two representative time periods: midday (12:00) and late afternoon (17:00). These time points were selected to capture contrasting environmental conditions, particularly thermal exposure, traffic patterns, and shading effects. Midday conditions typically correspond to higher temperatures and environmental stress, while late afternoon conditions are typically improved for walking due to reduced heat and increased shade. All dynamic variables were aligned with these two time periods, and continuous data were aggregated accordingly to ensure temporal consistency.

## 2.3 Walkability Model

The static component of walkability was calculated using the Walkability Index for Elderly Health (WIEH), which integrates urban tissue, urban scene, and urban safety variables and normalizes them by slope and stair conditions. The weighting scheme in Equation (1) follows Alves et al. (2020), assigning urban tissue the highest importance due to its direct influence on pedestrian movement, while urban scene and safety contribute to comfort and perceived security.

$$\text{WIEH} = (0.60 \times \text{Urban Tissue} + 0.16 \times \text{Urban Scene} + 0.24 \times \text{Safety}) / (0.50 \times \text{Slope} + 0.50 \times \text{Stair}) \quad (1)$$

To incorporate temporal dynamics, a Dynamic Walkability Score (DWS) in Equation (2) was developed by integrating the static index with time-dependent environmental variables. The static component was assigned a dominant weight (0.7) to preserve the fundamental role of infrastructure, while dynamic variables collectively account for 30% of the score. Among these, traffic was assigned the highest weight due to its direct influence on pedestrian safety, followed by air quality and environmental comfort factors such as temperature, humidity, shade, and lighting. The Dynamic Walkability Score (DWS) incorporates both spatial and temporal factors, calculated as:

$$\text{DWS} = 0.70 \times \text{WIEH} + 0.10 \times \text{Traffic} + 0.05 \times \text{AQI} + 0.025 \times \text{Temperature} + 0.025 \times \text{Humidity} + 0.05 \times \text{Shade} + 0.05 \times \text{Lighting} \quad (2)$$

Initial weights were assigned using expert judgment, informed by existing literature on elderly vulnerability to traffic exposure, thermal stress, visibility, and environmental pollution (Frank et al., 2010; Kenny et al., 2010; Oxley et al., 2017). This approach follows established practices in composite index construction when empirical weighting schemes are not available (OECD, 2008). To reduce subjectivity, the weighting structure was further evaluated using variance-based sensitivity analysis, enabling assessment of the robustness of walkability outcomes to variations in weight assumptions (Nguyen and Gigliarano, 2025). The results indicate that while absolute walkability values vary slightly under different weighting scenarios, the relative ranking of pedestrian segments remains stable, confirming the robustness of the model.

The resulting dynamic walkability scores were classified into five categories, ranging from not age-friendly to more age-friendly to facilitate interpretation and support practical applications in route planning and urban design.

## 2.4 Validation Approach

To evaluate the effectiveness of the proposed framework, a route-based validation was conducted by comparing model-derived walkability routes with pedestrian routes generated by Google Maps. This approach provides a behavioral reference by assessing how well the dynamic walkability model aligns with commonly used navigation systems.

For selected origin–destination (OD) pairs within the study area, shortest-path walking routes were first obtained from Google Maps, representing typical pedestrian navigation primarily based on distance and travel time. These routes were then compared with routes derived from the DWS using Dijkstra’s algorithm within a network analysis framework. In this implementation, each pedestrian network segment was assigned a cost value based on its walkability score, allowing the algorithm to identify optimal routes that minimize walkability cost rather than travel distance. This approach enables the identification of routes that prioritize safety, comfort, and environmental conditions. By transforming walkability scores into network costs, the model generates alternative paths that avoid segments with unfavorable conditions, providing a more suitable routing strategy for elderly pedestrians.

The comparison was performed using three indicators. First, route similarity was evaluated by measuring the spatial overlap between Google-based routes and model-derived routes. Second, average walkability scores along each route were calculated to assess differences in environmental quality. Third, key environmental exposures, including traffic conditions and thermal stress, were compared between routes at the selected time periods (12:00 and 17:00).

## 3. Results

The results present the spatial distribution of static walkability, the temporal variation captured by the dynamic model, and the validation of the proposed framework through route-based comparison with Google Maps.

### 3.1 Spatial Pattern of Static Walkability

The static walkability results reveal clear spatial differences across the three study areas. The hospital and campus environments exhibit higher baseline walkability, reflecting better pedestrian infrastructure, including wider sidewalks, more consistent surface quality, and greater availability of supporting facilities such as vegetation and signage. In contrast, the residential neighborhood shows lower walkability scores, primarily due to discontinuous sidewalks, limited pedestrian space, and the presence of obstacles.

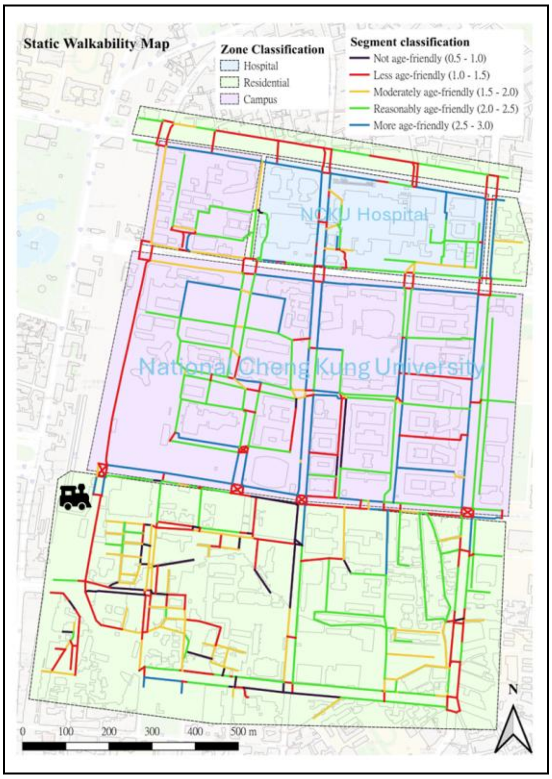


Figure 2. Static Walkability Map Highlighting Age-Friendly Routes.

The statistical analysis of static walkability in Table 2 reveals clear differences across the study areas. Overall, the mean WIEH score for all segments is 1.795, indicating moderate walkability conditions. Among the three urban contexts, the campus area exhibits the highest mean walkability score (2.039), followed by the hospital area (2.061), while the residential area shows a considerably lower mean value (1.648). The variability of walkability, as indicated by the standard deviation, is relatively consistent across areas, ranging from 0.511 to 0.559, suggesting comparable dispersion of conditions within each context. However, the range of values highlights greater heterogeneity in the campus area (0.796–3.000), indicating the presence of both highly walkable and less favorable segments. In contrast, the residential area shows a narrower but lower range (0.592–2.720), reflecting generally constrained pedestrian conditions. The 95% confidence intervals further confirm these differences, with higher intervals observed in the campus and hospital areas compared to the residential area. These results demonstrate that institutional environments provide more favorable baseline walkability, while residential areas present greater limitations for elderly pedestrians.

| | All | Hospital | Campus | Residential |
|---|---|---|---|---|
| **Segment Count** | 605 | 72 | 181 | 303 |
| **Static WIEH - Mean** | 1.795 | 2.061 | 2.039 | 1.648 |
| **Static WIEH - Standar Deviation** | 0.551 | 0.559 | 0.532 | 0.511 |
| **Range** | [0.507, 3.000] | [0.507, 3.000] | [0.796, 3.000] | [0.592, 2.720] |
| **95% Confidence Interval** | [1.751, 1.839] | [1.932, 2.190] | [1.961, 2.117] | [1.590, 1.706] |

Table 2. Descriptive statistics of static walkability (WIEH) across all segments and study areas.

### 3.2 Temporal Variation of Dynamic Walkability

The results in Tables 3, 4, and 5 demonstrate that walkability varies both spatially and temporally across the study areas. Overall, institutional environments such as hospitals and campuses exhibit consistently higher walkability than residential areas. The mean static walkability (WIEH) is highest in the hospital (2.061) and campus (2.039) areas, while the residential area shows a lower mean value (1.648). The integration of dynamic environmental factors further reveals that walkability is not fixed but influenced by changing conditions throughout the day. These findings confirm that relying solely on static indicators may underestimate the variability of pedestrian suitability, particularly for elderly users.

From a temporal perspective, dynamic walkability shows noticeable variation between the two analyzed time periods (12:00 and 17:00). In the hospital area, mean DWS values range from 2.114 to 2.209, indicating relatively stable conditions, while the campus area shows similar patterns with values between 2.115 and 2.208. In contrast, the residential area exhibits lower values, ranging from 1.809 to 1.900, and shows greater sensitivity to environmental changes. Midday conditions generally reflect higher environmental stress, whereas late afternoon conditions tend to improve walkability due to reduced heat and better shading. Although the differences are moderate, they highlight the influence of temporal factors on pedestrian comfort.


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Across urban contexts, clear differences are observed in both baseline and dynamic walkability. The hospital and campus areas maintain relatively high and stable walkability, supported by continuous sidewalks and better pedestrian infrastructure. Standard deviation values are relatively consistent across areas (approximately 0.36–0.56), indicating comparable variability within each context. However, the residential area shows both lower mean values and greater fluctuations, reflecting the combined effects of limited infrastructure and environmental exposure. Minimum values further indicate that certain segments remain less suitable for elderly pedestrians regardless of time.

| Hospital | Weekday | | Weekend | |
|---|---|---|---|---|
| | 12:00 | 17:00 | 12:00 | 17:00 |
| **Mean** | 2.209 | 2.194 | 2.114 | 2.119 |
| **Standard Deviation** | 0.399 | 0.391 | 0.412 | 0.407 |
| **Range** | [1.155, 2.950] | [1.130, 2.875] | [1.105, 2.844] | [1.055, 2.800] |
| **Confidence Interval (95%)** | [2.117, 2.301] | [2.104, 2.284] | [2.019, 2.209] | [2.025, 2.213] |

Table 3. Descriptive statistics of dynamic walkability (DWS) in the hospital area.

| Campus | Weekday | | Weekend | |
|---|---|---|---|---|
| | 12:00 | 17:00 | 12:00 | 17:00 |
| **Mean** | 2.208 | 2.191 | 2.172 | 2.115 |
| **Standard Deviation** | 0.397 | 0.379 | 0.387 | 0.386 |
| **Minimum** | [1.107, 2.900] | [1.282, 2.875] | [1.257, 2.760] | [1.207, 2.800] |
| **Confidence Interval (95%)** | [2.150, 2.266] | [2.136, 2.246] | [2.116, 2.228] | [2.059, 2.171] |

Table 4. Descriptive statistics of dynamic walkability (DWS) in the campus area.

| Residential | Weekday | | Weekend | |
|---|---|---|---|---|
| | 12:00 | 17:00 | 12:00 | 17:00 |
| **Mean** | 1.900 | 1.877 | 1.855 | 1.809 |
| **Standard Deviation** | 0.373 | 0.362 | 0.372 | 0.370 |
| **Minimum** | [1.064, 2.726] | [1.087, 2.701] | [1.018, 2.655] | [0.890, 2.548] |
| **Confidence Interval (95%)** | [1.858, 1.942] | [1.836, 1.918] | [1.813, 1.897] | [1.767, 1.851] |

Table 5. Descriptive statistics of dynamic walkability (DWS) in the residential area.

In summary, the findings emphasize that walkability is determined by the interaction between built environment characteristics and time-dependent environmental conditions. This integrated perspective provides a more comprehensive understanding of pedestrian conditions and supports the development of adaptive, time-sensitive, and elderly-oriented urban planning strategies.

### 3.3 Comparison between Static and Dynamic Walkability

The comparison between static and dynamic walkability in Table 6 highlights the combined influence of built environment characteristics and temporal conditions on pedestrian suitability. Overall, institutional environments such as the hospital and campus maintain relatively high baseline walkability, with mean static values of 2.061 and 2.039, respectively, compared to a lower value of 1.648 in the residential area. The integration of dynamic environmental factors results in consistent improvements across all contexts, indicating that walkability is not a fixed attribute but varies with changing environmental conditions.

| Urban Type | Comparison | Weekday | | Weekend | |
|---|---|---|---|---|---|
| | | 12:00 | 17:00 | 12:00 | 17:00 |
| **Hospital** | Mean Change | +0.148 | +0.133 | +0.053 | +0.058 |
| | Percent Change | +7.2% | +6.5% | +2.6% | +2.8% |
| **Campus** | Mean Change | +0.169 | +0.152 | +0.133 | +0.076 |
| | Percent Change | +8.3% | +7.5% | +6.5% | +3.7% |
| **Residential** | Mean Change | +0.252 | +0.229 | +0.207 | +0.161 |
| | Percent Change | +15.3% | +13.9% | +12.6% | +9.8% |

Table 6. Static–dynamic walkability changes across urban areas and time periods.

In the hospital and campus areas, dynamic walkability shows moderate increases compared to the static baseline. In the hospital area, mean changes (ΔWIEH) range from +0.053 to +0.148, corresponding to percentage increases between +2.6% and +7.2%. Similarly, the campus area exhibits ΔWIEH values between +0.076 and +0.169, with percentage changes ranging from +3.7% to +8.3%. These relatively stable improvements suggest that well-developed pedestrian infrastructure provides a consistent foundation, where dynamic environmental conditions enhance walkability without substantially altering overall spatial patterns.

In contrast, the residential area demonstrates significantly larger changes, with ΔWIEH values ranging from +0.161 to +0.252 and percentage increases between +9.8% and +15.3%. This indicates that dynamic factors such as temperature, shading, and traffic conditions have a stronger relative influence in areas with


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weaker infrastructure. Temporal variation is also evident, with greater improvements generally observed during midday (12:00) compared to late afternoon (17:00), particularly on weekdays. These findings suggest that environmental conditions can partially compensate for infrastructural limitations, but do not fully overcome them.

At the segment level, these changes lead to the reclassification of pedestrian suitability across time periods. Segments that are categorized as less age-friendly under static conditions or during less favorable periods can shift to more suitable categories under improved environmental conditions. However, segments with poor structural characteristics, such as narrow or absent sidewalks, remain consistently unsuitable regardless of temporal improvements. Overall, the results emphasize that walkability is shaped by the interaction between infrastructure quality and time-dependent environmental factors, with dynamic conditions playing a particularly important role in more constrained urban environments.

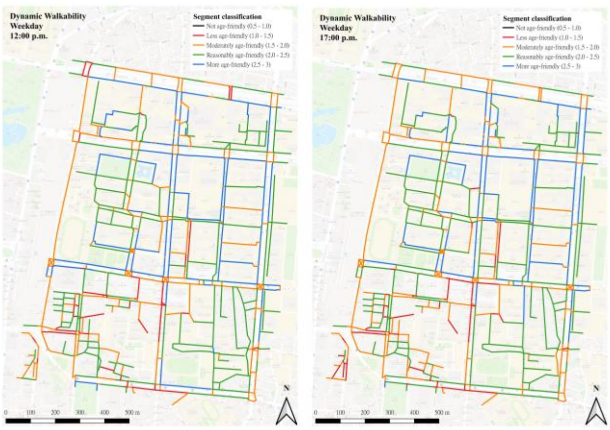


Figure 4. Dynamic Walkability Maps Based on Pedestrian Routes at 12:00 p.m. (Left) and 5:00 p.m. (Right) on Weekdays.

### 3.4 Route-Based Validation

The effectiveness of the proposed dynamic walkability framework was evaluated through a route-based validation by comparing model-derived routes with pedestrian routes generated by Google Maps. The Google Maps routes serve as a baseline, representing shortest-distance or time-efficient paths, while the model-derived routes were generated using Dijkstra’s algorithm within a QGIS (QNEAT3) network analysis framework, where segment weights were defined based on the DWS.

The comparison reveals systematic differences in route selection between the two approaches. Google Maps routes tend to prioritize direct connections and shorter distances, often following major roads with higher traffic exposure and limited shading. In contrast, the DWS-based routes incorporate environmental and comfort-related factors, resulting in alternative paths that avoid segments with lower walkability. As illustrated in Figure 5, the model-derived routes frequently pass through campus areas or secondary streets with better pedestrian infrastructure, increased vegetation, and reduced exposure to traffic.

Temporal variation further influences routing outcomes. At 12:00, when environmental stress is higher due to elevated temperatures and reduced thermal comfort, the DWS-based routes show greater deviation from the shortest path, prioritizing shaded and less congested segments. At 17:00, when conditions become more favorable, the differences between routes are reduced, and the selected paths tend to converge toward more direct routes. This pattern indicates that the influence of environmental factors on route selection is time-dependent and more pronounced under unfavorable conditions.

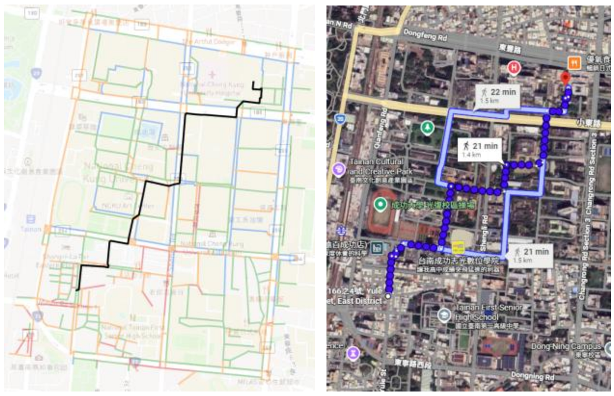

Figure 5. Comparison of pedestrian routes generated by the DWS-based model (left) and Google Maps (right).

Quantitative comparison supports these observations. As shown in Table 7, the DWS-based routes consistently achieve higher average walkability scores than Google Maps routes, with improvements exceeding 10% in residential contexts, despite modest increases in travel distance. In contrast, differences are smaller in the hospital and campus areas, where baseline walkability is already high and more stable. These findings suggest that the benefits of dynamic routing are more significant in areas with lower infrastructure quality.

| OD Pair | Time | Route Type | Distance (km) | Avg DWS | ΔDWS (%) |
|---|---|---|---|---|---|
| **OD1 (Campus–Hospital)** | 12:00 | Google Maps | 1.50 | 2.03 | – |
| | | DWS Route | 1.64 | 2.18 | +7.4% |
| | 17:00 | Google Maps | 1.50 | 2.08 | – |
| | | DWS Route | 1.60 | 2.20 | +5.8% |
| **OD2 (Campus–Residential)** | 12:00 | Google Maps | 1.40 | 1.72 | – |
| | | DWS Route | 1.58 | 1.98 | +15.1% |
| | 17:00 | Google Maps | 1.40 | 1.85 | – |
| | | DWS Route | 1.52 | 2.05 | +10.8% |
| **OD3 (Hospital–Residential)** | 12:00 | Google Maps | 1.60 | 1.80 | – |
| | | DWS Route | 1.75 | 2.06 | +14.4% |
| | 17:00 | Google Maps | 1.60 | 1.88 | – |
| | | DWS Route | 1.70 | 2.08 | +10.6% |

Table 7. Comparison of Google Maps routes and DWS-based routes at 12:00 and 17:00 for selected OD pairs.

Overall, the route-based validation demonstrates that incorporating dynamic environmental variables into network analysis provides a more realistic representation of pedestrian decision-making. By prioritizing safety, comfort, and environmental quality, the proposed framework offers a more suitable routing strategy for elderly pedestrians compared to conventional shortest-path approaches.

## 4. Discussion

The results of this study reinforce the growing recognition that walkability is not a static attribute but a condition that varies over time. While traditional approaches emphasize fixed built-environment characteristics (Frank et al., 2010; Alves et al., 2020), the findings demonstrate that environmental factors such as temperature, air quality, and traffic conditions can substantially alter pedestrian suitability throughout the day. This aligns with recent studies highlighting the importance of incorporating temporal variability into walkability assessments (Carra et al., 2022; Khalil & Mohamed, 2023). In particular, the observed differences between midday (12:00) and late afternoon (17:00) confirm that time-dependent environmental conditions play a critical role in shaping elderly walking experiences.

The analysis also shows that the influence of dynamic factors varies across urban contexts. In residential areas, where pedestrian infrastructure is relatively limited, environmental conditions such as heat exposure and lack of shading significantly affect walkability. This finding is consistent with previous research indicating that elderly pedestrians are more sensitive to environmental stressors, including thermal discomfort and exposure to hazards (Kenny et al., 2010; Oxley et al., 2018). In contrast, the hospital and campus areas exhibit more stable walkability conditions due to better infrastructure and supportive design elements, which aligns with studies emphasizing the role of high-quality pedestrian infrastructure in enhancing walkability (Woldeamanuel & Kent, 2016; Rosenberg et al., 2013). These results suggest that while improving infrastructure remains essential, environmental design interventions such as shading and microclimate adaptation are equally important in less-developed areas.

The route-based validation further highlights the limitations of conventional navigation systems. Similar to previous accessibility-based approaches such as Walk Score (Horak et al., 2022), Google Maps primarily optimizes routes based on distance and travel time, without accounting for environmental comfort or safety. The results show that model-derived routes differ significantly under unfavorable conditions, particularly at midday, where heat exposure and air quality become critical constraints. This supports findings from recent studies that emphasize the need for user-centered and context-aware routing models (Chen et al., 2022; Lai et al., 2019). By integrating environmental variables into the routing process, the proposed framework provides a more suitable representation of pedestrian decision-making for elderly users.

From a planning perspective, the findings underscore the importance of integrating temporal and environmental considerations into urban design strategies. Previous studies have highlighted the importance of age-friendly environments that support mobility and health among older adults (Yen and Anderson, 2012; Shigematsu et al., 2009). This study extends that perspective by demonstrating that walkability is not only a function of spatial design but also of temporal conditions. Incorporating elements such as shading, vegetation, and climate-responsive design can significantly enhance pedestrian comfort, particularly in hot and humid environments such as Taiwan. Moreover, the results suggest that future pedestrian routing systems should move beyond shortest-path optimization and incorporate dynamic environmental factors to better support vulnerable populations.

Despite its contributions, this study has several limitations. The analysis is based on a specific urban context in Tainan, Taiwan, where climatic conditions, urban form, and pedestrian infrastructure may differ from other regions. As noted in previous studies (Chen et al., 2022; Lai et al., 2019), walkability models often require contextual adaptation to reflect local conditions. In addition, the weighting scheme, although informed by literature and expert judgment (OECD, 2008), may require recalibration for different geographic contexts. The validation approach, based on comparison with Google Maps routes, provides a useful behavioral reference but does not directly capture actual pedestrian choices. Future research should incorporate user-based data, such as GPS tracking or surveys, to further validate and refine the proposed framework.

## 5. Conclusion

This study proposed a network-based dynamic walkability framework that integrates static built environment characteristics with time-dependent environmental factors to better represent pedestrian conditions for elderly users. By combining infrastructure-based indicators with dynamic variables such as temperature, air quality, traffic, shade, and lighting, the model captures both spatial and temporal variability in walkability.

The results demonstrate that dynamic walkability provides a more comprehensive understanding of pedestrian environments than static approaches alone. Temporal analysis reveals that walkability conditions vary significantly between midday and late afternoon, with improvements of up to over 15% observed under more favorable conditions. These variations are particularly pronounced in residential areas, where environmental factors have a stronger influence due to weaker baseline infrastructure.

The route-based validation shows that the proposed model generates walking routes that differ from conventional navigation systems by prioritizing safety, comfort, and environmental quality. This highlights the limitations of shortest-path approaches and underscores the need for more user-centered and context-aware routing strategies.

Overall, the findings suggest that incorporating temporal dynamics into walkability assessment can support more inclusive and health-oriented urban planning. The proposed framework provides a foundation for developing time-sensitive pedestrian routing systems and can be extended to support multi-objective optimization approaches for elderly mobility. Future work will focus on integrating the model into routing algorithms and validating the results using real-world pedestrian behavior data.

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