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Calculation of Walking Distance Accessibility Range for Urban Rail Transit Stations Based on Walking Grids

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Abstract: Common methods for calculating the accessible walking distance of urban rail transit stations, such as buffer analysis and network analysis, have limitations in terms of computational accuracy, spacious walking space simulation, scenario applicability, and particularly the capability to support planning scheme evaluations. This paper presents a pedestrian surface that represents urban public walking spaces, assigns elevation tags to distinguish multi-level walking spaces, and defines connectivity rules. Walking speeds are adjusted in specific areas, including pedestrian overpasses, ramps, stairs, and signal-controlled intersections. Walking grids are created with a resolution of 0.1’’ × 0.1’’ (longitude difference × latitude difference) and coded using an 18-digit system. A grid-based search algorithm is proposed, which uses the entrances and exits of urban rail transit stations as starting points to search and determine the maximum accessible walking distance within a given distance or time threshold. Taking Chongqing’s urban rail transit stations as a case study, current conditions and planning schemes are evaluated. The results indicate that due to constraints such as mountainous terrain and barriers posed by arterial roads and residential complexes, the 10-minute accessible walking distance for Chongqing’s urban rail transit stations covers only 69% of the area within an 800-meter buffer zone. The application of this method demonstrates its capability to accurately simulate the implementation effect of spacious walking spaces such as plazas and open residential areas, as well as terrain altitude variations, multi-level urban road interchanges, and pedestrian crossing facilities.
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Keywords: urban rail transit; accessible walking distance; walking grid; grid search; grid encoding

0 Introduction

As the scale of urban rail transit networks in major cities continues to grow, green and intensive travel modes primarily relying on “urban rail transit + walking” are becoming increasingly prevalent. Walking serves as an important feeder mode for urban rail transit. For instance, in Beijing, the proportions of passengers walking before they enter and after they exit urban rail transit stations are 66% and 75%, respectively [1]. Due to the mountainous terrain in the central urban area of Chongqing, non-motorized vehicles are less common, and the proportion of passengers walking to and from stations reaches as high as 89%. Yang et al. [2] noted that the attractiveness of urban rail transit stations diminishes with the increasing distance from the station. For more than a certain range, passengers’ willingness to walk decreases sharply. The acceptable time for passengers to walk to an urban rail transit station does not exceed 12 min, and the acceptable distance does not exceed 1 km. Typically, a walking distance of 800 m or a walking time of 10 min is considered a reasonable walking attraction range for urban rail transit stations [3]. Given a specific time (distance) threshold, the actual accessible walking distance of each station may vary significantly due to factors such as road networks, terrain, and residential barriers. Accurate assessment of the accessible walking distance of stations during the planning and design phase can effectively support passenger flow forecasting, thereby facilitating rational planning of urban rail transit networks and station layout. After the completion of urban rail transit, we can attract more passengers by expanding the accessible walking distance, thereby enhancing the operational efficiency of urban rail transit.

Common methods for calculating the accessible walking distance of urban rail transit stations include buffer zone analysis and network analysis:

1) The buffer zone analysis method takes an urban rail transit station as the center and a given distance threshold as the radius to define a circular buffer zone as the accessible walking distance. This method is standardized, simple to operate, and widely applicable, and is the main calculation method for evaluating the public transport coverage level in relevant policies and standards [4]. It is frequently applied in urban macro-scale research. For example, in assessing the suitability of the transit oriented development (TOD) model for urban rail transit stations in Melbourne, Australia, Jeffrey et al. [5] used an 800 m radius buffer zone as the service area of the station; Bivina et al. [6] also adopted the same method in evaluating the walking accessibility of urban rail transit

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stations in Delhi, India; Considering the impact of Beijing's grid road network, Zhai et al. [7] made some improvements to the buffer zone analysis method, defined a 1 km × 1 km grid, and calculated the Manhattan distance between the grid and the nearest urban rail transit station, evaluating the walking convenience from residential areas to urban rail transit stations.

2) The network analysis method starts from urban rail transit stations or other facility points and ends at surrounding demand points, seeking the shortest path based on the walking grid. Through repeated attempts, it determines the maximum accessible walking distance under a given distance or time threshold. For example, Hua et al. [8] first constructed a road network when they assessed the walking accessibility of community commercial facilities, and then used the network analysis tool provided by ArcGIS software to obtain the time from each residential area to the community commercial facilities. Yuan et al. [9] generated the walking and bus travel distances from each population grid to urban rail transit stations by establishing urban road networks and bus line networks with the help of ArcGIS software. Pei et al. [10] generated the service range of bus stops in different circles. Stoia et al. [11] calculated the service ranges of parks for 5 min, 10 min, 15 min, and 30 min walking and cycling using the service area analysis tool provided by ArcGIS software. In assessing the accessibility of the Hong Kong subway, He [12] used the shortest path algorithm of ArcGIS to calculate the walking time from plots to urban rail transit stations.

With the opening of Internet maps, platforms and data such as OpenStreetMap (OSM), Amap, and Baidu Maps can provide convenient analysis services for the application of network analysis methods, eliminating the need for users to engage in tedious data collection and network modeling tasks. For example, Shen et al. [13] centered on the geometric midpoint of urban rail transit stations and set walking point arrays every 10 m. Based on the Application Programming Interface (API) of Amap, they obtained the shortest time for each point array to reach the entrance and exit of the station, thereby determining the accessible walking distance. Dai et al. [14] used the Amap API as the basis for calculating walking paths and time consumption, and analyzed the 10 min accessible walking distance of each urban rail transit station in Shenzhen. Zhang et al. [15] calculated the shortest walking time consumption from each residential building to the nearest bus stop through the Baidu Maps API to analyze the coverage of bus stops in residential areas. Tarkowski et al. [16] used OSM datasets and QGIS software to calculate the walking time from each residential area to public transportation stations, thus evaluating the population covered by public transportation services.

Although the buffer zone analysis method is simple, it cannot reflect factors such as dead-end roads, separated arterial roads, topographical elevation differences, and barriers in enclosed residential areas due to its lack of consideration for actual walking paths, resulting in significant errors and unsuitability for meso- and micro-level refined assessments. The network analysis method requires the construction of a walking grid, which typically abstracts the walking space as network node connections, limiting the walking flow lines of all passengers to a single path represented by the connection lines. When there are spacious walking spaces such as walking plazas, open residential areas, and walking streets, passengers in different directions (which can be expressed by the lines connecting their entry and exit locations) have different flow lines, and it does not match the actual situation using a single path. When the starting and ending points of the walking route are located outside the network nodes (margins), it is necessary to first project the starting and ending points onto the nearest margin before conducting path search and distance calculation. Due to blockages caused by buildings and fences, pedestrians may need to take detours, so the actual distance to the network may exceed the projected distance, leading to an underestimation of the total walking distance. In addition, network analysis methods based on Internet maps are usually only suitable for assessing the current status and are difficult to support the testing and evaluation of planning schemes.

Given this, this paper proposed a method for calculating the accessible walking distance of urban rail transit stations based on walking grids. All walking spaces were abstracted as pedestrian surfaces, and the accessible walking distance was calculated using the grid-based search algorithm by dividing the walking grids and encoding the grids. This method comprehensively considered factors such as terrain elevation differences, road slopes, and street crossing facilities, and can accurately simulate the implementation effects of parks, squares, open residential areas, walking pathways, and walking entrances and exits, obtaining the true accessible walking distance of urban rail transit stations, which can be used for both the evaluation of the current built environment and the testing and evaluation of planning schemes.

1 Walking space modeling

1.1 Construction of the pedestrian surface

The walking space refers to the physical space designated for pedestrians to traverse. Urban public walking spaces can be categorized into five types: sidewalks and walking crossing facilities on traffic roads, residential roads, walking streets and dedicated footpaths, setback spaces of buildings facing the street, and walking spaces within open plots. With the aid of geographic information software, pedestrian surfaces were generated based on the projections of each type of walking space (see Tab. 1). Pedestrian surfaces were separately created and marked for walking ramps and stairways, walking crossings, three-dimensional crossing facilities, and the upper and lower levels and overlapping areas of multi-level walking spaces, thus facilitating the setting of different elevation labels and walking speed reduction factors. A schematic diagram of the pedestrian surfaces around urban rail transit stations is shown in Fig. 1.

Tab. 1 Classification of urban public walking spaces and methods for constructing pedestrian surfaces

Name	Definition	Method for constructing pedestrian surface
Sidewalks and walking crossing facilities on traffic roads	Roads with a large traffic volume, where pedestrians are not allowed to cross at will and can only cross the street through pedestrian crossings, multi-level pedestrian crossing facilities (pedestrian overpasses, pedestrian underpasses), etc.	Take the area between the curbstone line and the road red line, the marking area of pedestrian crossings, and the projection area of the three-dimensional crossing facilities
Residential roads	Some secondary (branch) roads with a low traffic volume and no central separation, where pedestrians are allowed to cross the street	Take the area between the red lines of the road
Walking streets and dedicated footpaths	Streets, pedestrian ramps, step roads, etc. exclusively for pedestrian traffic	Take the area between the red lines of pedestrian streets or dedicated footpaths
Setback spaces of buildings facing the street	The space left by the setback of buildings facing the street for pedestrian passage	Take the actual setback area of the building
Walking spaces within open plots	Squares, parks, commercial and office areas, open residential communities, hospitals, universities, sports venues, etc. where pedestrians are allowed to pass through	Take the internal roads and pedestrian paving areas of open plots; Commercial plots may include building foundations; Other types of plots do not include building foundations

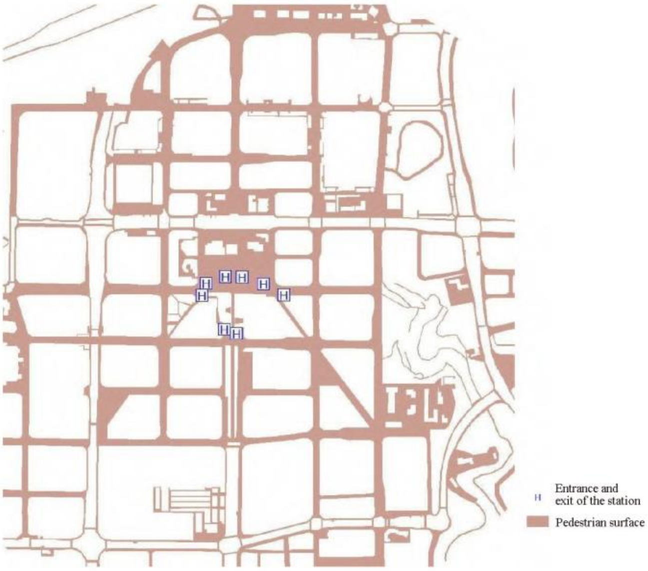

Fig. 1 Illustration of pedestrian surfaces in the surrounding area of urban rail transit stations

1.2 Elevation and connectivity rule settings

The area of urban road grade-separated intersections (hereinafter referred to as “interchanges”) typically includes independent walking spaces on both upper and lower levels, where their planar projections overlap but are not directly connected. To accurately reflect the multi-level spatial relationships, the walking spaces were divided into flat slope areas, upper areas, lower areas, and overlapping areas. The relative relationship between the upper and lower levels was described through the elevation labels, where the elevation of the flat slope area was set to 0, that of the upper-level area was set to +1, that of the lower-level area was set to –1, and that of the overlapping area was set to ±1. It was defined that adjacent walking spaces with the same elevation can be connected (including 0 and 0, 1 and 1, as well as –1 and –1), and the flat slope area can be connected to both the upper and lower levels (including 0 and +1, as well as 0 and –1). The walking spaces on the upper and lower levels of the overlapping area were not directly connected (i.e., +1 and –1 were not connected). The elevation label settings for the overpass (underpass) area of a typical interchange are shown in Fig. 2a, and the elevation label for the walking bridge area is shown in Fig. 2b (similarly, the elevation label for the walking subway area can be set).

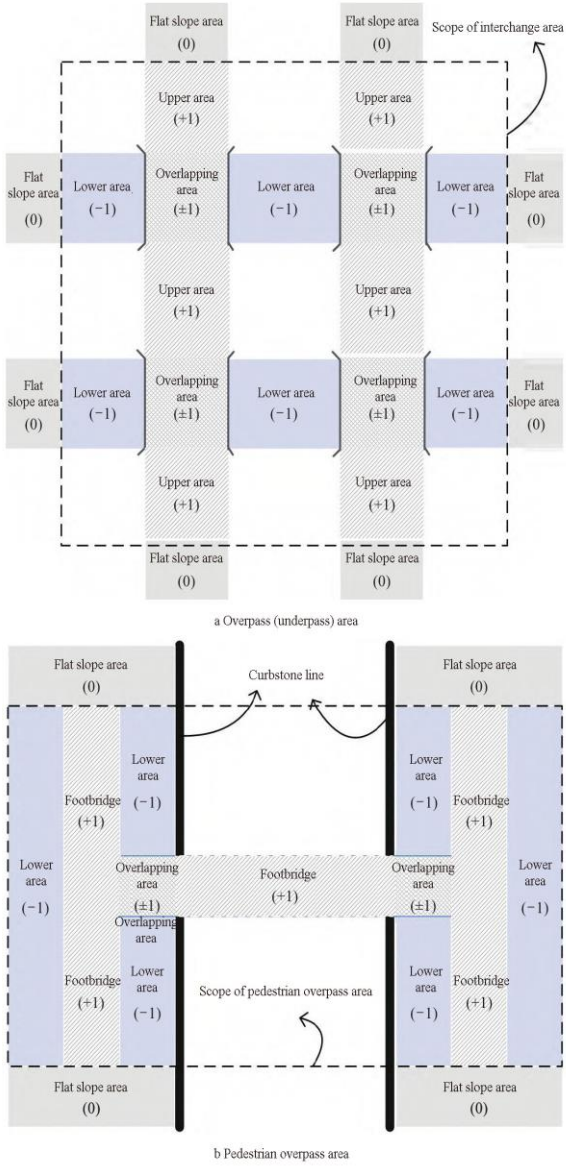

Fig. 2 Illustration of elevation settings for urban road interchange areas

1.3 Reduction of walking speed

In addition to being influenced by passengers’ physical conditions (age, gender, and health level), the walking speed is affected by factors such as the slope, traffic lights, walking density, and parked vehicles that occupy the roadways. The walking speed of adults on a flat slope is approximately 1.0 to 1.4 $m \cdot s^{-1}$ [17], and it decreases to about 1.01 to 1.26 $m \cdot s^{-1}$ [18] when they are subjected to external disturbances, such as crowds gathering or vehicle interference at intersections. To characterize the differences in the walking speed across different areas, reductions are made based on the walking speed on a flat slope for specific areas such as walking overpasses and underpasses, walking ramps and stairways, and walking crossings at signal-controlled intersections. The calculation formula for the walking speed on the projected surface of a ramp is as follows:

$$v_p = v_s / \sqrt{1+\sigma^2}\ , \tag{1}$$

where v_p represents the walking speed on the ramp projection surface ($m \cdot s^{-1}$); v_s represents the walking speed on the slope surface ($m \cdot s^{-1}$); σ represents the slope value, %. The ratio of the walking speed on the ramp projection surface to that on a flat slope (taken as 1.3 $m \cdot s^{-1}$) is taken as the reduction factor for the walking speed on the ramp projection surface (see Tab. 2).

Tab. 2 Walking speed and reduction factors for ramp projection surfaces

Type		Slope value/%	Slope walking speed [19]/($m \cdot s^{-1}$)	Walking speed of ramp projection surface/($m \cdot s^{-1}$)	Reduction factor of walking speed
Ramp	Flat slope	0~3.5	1.30	1.30	1.00
	Gentle slope	>3.5–8.0	1.01	1.01	0.78
	Mid gentle slope	>8.0–23.0	0.90	0.90	0.69
	Middle slope (staircase)	>23.0–33.0	0.80	0.76	0.58
	Steep slope (staircase)	>33.0–45.0	0.68	0.62	0.48
Pedestrian overpass and underpass	Staircase	≤50.0	0.57	0.51	0.39
	Electric staircase	<30.0	0.75	0.72	0.55
		30.0–35.0	0.50	0.47	0.36

Taking into account the waiting time of pedestrians, the formula for calculating the pedestrian crossing speed at a signal-controlled intersection is:

$$v_c = v_r / \left(1 + v_r w / s\right)\ , \tag{2}$$

where v_c represents the reduced pedestrian crossing speed/($m \cdot s^{-1}$); v_r represents the unreduced pedestrian crossing speed/($m \cdot s^{-1}$); w represents the average waiting time for the red light/s; s represents the length of the pedestrian crossing/m. The ratio of the reduced pedestrian crossing speed to the free walking speed on a flat slope (taken as 1.3 $m \cdot s^{-1}$) is the pedestrian crossing speed reduction factor at signal-controlled intersections. In this paper, the unreduced pedestrian crossing speed took 1 $m \cdot s^{-1}$, and the average waiting time for red lights took 45 s (135 s for double crossings). The walking crossing walking speed and reduction factor at signal-controlled intersections are shown in Tab. 3.

Tab. 3 Pedestrian crossing speeds and reduction factors at signal-controlled intersections

Lane number	Length of pedestrian crossing/m	Unreduced pedestrian crossing speed/($m \cdot s^{-1}$)	Average waiting time for red light/s	Reduced pedestrian crossing speed/($m \cdot s^{-1}$)	Walking speed reduction factor
Two lanes (single crossing)	8	1.0	45	0.15	0.12
Four lanes (single crossing)	16	1.0	45	0.26	0.20
Six lanes (double crossing)	24	1.0	135	0.15	0.12
Eight lanes (double crossing)	32	1.0	135	0.19	0.15

2 Construction of walking grid

2.1 Grid division and coding

The grids were divided based on the 1 : 5 000 topographic map of China [20] (with a longitude difference of 1’52.5” and a latitude difference of 1’15”). As shown in Fig. 3, each map is divided into 750 rows and 1 125 columns according to a longitude difference of 0.1” and a latitude difference of 0.1”, resulting in a total of 843 750 grids. The grid projection sizes vary in different latitude regions, where the grid size in the region at 30°N is approximately 2.68 m × 3.09 m. The grids covered by the walking space projection plane are defined as walking grids. For interchange areas, the corresponding walking grids of the overlapping area, upper area, and lower area are extracted separately, and corresponding elevation labels are set. For areas where the walking speed needs to be reduced, the walking grids are extracted separately, and walking speed reduction factors are set according to the type. Walking grids with an elevation label other than 0 or a walking speed reduction factor other than 1 are defined as special walking grids.

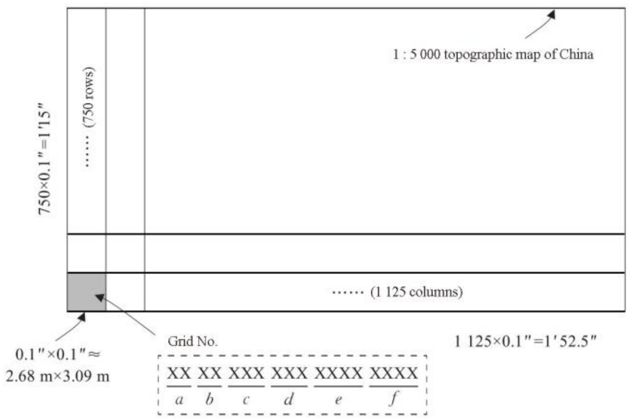

Fig. 3 Division of walking grids based on a 1 : 5 000 topographic map

The 18-digit grid coding was adopted. The first 4 digits represent the number of the 1 : 1 000 000 topographic map sheet where the grid is located, where a is the row number (numeric code) and b is the column number. If either a or b is less than 2 digits, the left side is padded with zeros. The digits 5 to 10 represent the number of the 1 : 5 000 topographic map sheet where the grid is located, where c is the row number and d is the column number. If either c or d is less than 3 digits, the left side is padded with zeros. The digits 11 to 18 represent the row and column numbers of the grid in the 1 : 5 000 topographic map, where e is the row number and f is the column number. If either e or f is less than 4 digits, the left side is padded with zeros. The calculation formula is as follows:

$$a=\left[\varphi/4°\right]+1\text{ ,} \tag{3}$$

$$b=\left[\lambda/6°\right]+31\text{ ,} \tag{4}$$

$$c=4°/1'15''-\left[\left(\varphi-4°(a-1)\right)/1'15''\right]\text{ ,} \tag{5}$$

$$d=\left[\left(\lambda-6°(b-31)\right)/1'52.5''\right]+1\text{ ,} \tag{6}$$

$$e=1'15''/0.1''-\left[\left(\varphi-4°(a-1)-1'15''(192-c)\right)/0.1''\right]\text{ ,} \tag{7}$$

$$f=\left[\left(\lambda-6°(b-31)-1'52.5''(d-1)\right)/0.1''\right]+1\text{ ,} \tag{8}$$

where, φ represents the latitude of the lower left corner of the grid; λ represents the longitude of the lower left corner of the grid, and [] denotes the floor operation.

2.2 Adjacent grid coding computation

Quick solution of adjacent grid encodings is the premise of grid search. Assuming the current grid encoding is g_i, the calculation method for 8 adjacent grid encodings g_j (j = 1, 2, ⋯, 8) is as follows:

1) The grid row and column numbers are extracted from the grid code. The 1st to 2nd, 3rd to 4th, 5th to 7th, 8th to 10th, 11th to 14th, and 15th to 18th characters of the grid code g_i are successively extracted, and they are parsed to obtain the grid row number $m(a_i, c_i, e_i)$ (composed of three-level row numbers) and column number $n(b_i, d_i, f_i)$ (composed of three-level column numbers), shortly denoted as (m_i, n_i).

2) The row and column indices (m_i, n_i) are offset to obtain the row and column indices and codes of adjacent grids. Let $m_i \pm 1$ denote a northward (southward) shift of one row, and $n_i \pm 1$ denote an eastward (westward) shift of one column. The row and column offset rules for 8 adjacent grids are shown in Fig. 4, and the calculation rules for the offset row and column indices are shown in Tab. 4.

3 Accessible range search based on walking grid

3.1 Variable definition and initialization

We define $W = \{g_i\}$ as the set of walking grids, S as the set of special walking grids, $s_i(g_i, h_i, r_i)$ as the label of the i-th grid in set S, P as the set of grids to be traversed, R as the set of traversed grids, and $p_i(g_i, h_i, r_i, l_i, t_i, k_i)$ (denoted as p_i) as the label of the ith grid in set P or R, where g_i is the grid code of the ith grid; h_i is the elevation of the ith grid; r_i is the walking speed reduction factor of the ith grid; l_i is the distance from the i-th grid to the nearest entrance/exit of urban rail transit station in m; t_i is the time from the i-th grid to the nearest entrance/exit of urban rail transit station, in s, and k_i is the number of the nearest entrance/exit of urban rail transit station to the i-th grid.

Northwest direction $(m_i+1,\ n_i-1)$	North direction $(m_i+1,\ n_i)$	Northeast direction $(m_i+1,\ n_i+1)$
West direction $(m_i,\ n_i-1)$	Current grid $(m_i,\ n_i)$	East direction $(m_i,\ n_i+1)$
Southwest direction $(m_i-1,\ n_i-1)$	South direction $(m_i-1,\ n_i)$	Southeast direction $(m_i-1,\ n_i+1)$

Fig. 4 Offset rules for numbering adjacent grid rows and columns

Tab. 4 Calculation rules for row and column numbers after adjacent grids offset

Offset direction	Offset rule	Calculation of row and column numbers
Offset northward by one row	$m_j=m_i+1$	① $e_j=e_i+1$; ② If $e_j>750$, then $e_j=e_j\%750$, $c_j=c_i+1$; ③ If $c_j>192$, then $c_j=c_j\%192$, $a_j=a_i+1$
Offset southward by one row	$m_j=m_i-1$	① $e_j=e_i-1$; ② If $e_j\leqslant 0$, then $e_j=750$, $c_j=c_i-1$; ③ If $c_j\leqslant 0$, then $c_j=192$, $a_j=a_i-1$
Offset eastward by one column	$n_j=n_i+1$	① $f_j=f_i+1$; ② If $f_j>1\ 125$, then $f_j=f_j\%1\ 125$, $d_j=d_i+1$; ③ If $d_j>192$, then $d_j=d_j\%192$, $b_j=b_i+1$
Offset westward by one column	$n_j=n_i-1$	① $f_j=f_i-1$; ② If $f_j\leqslant 0$, then $f_j=1\ 125$, $d_j=d_i-1$; ③ If $d_j\leqslant 0$, then $d_j=192$, $b_j=b_i-1$

Note: % represents the remainder operation.

Suppose there are N entrances and exits in an urban rail transit station. Corresponding walking grids i (i = 1, 2, ⋯, N) are extracted according to the coordinates of each entrance and exit in turn. We take $h_i = 0$, $r_i = 1$, $l_i = 0$, $t_i = 0$, $k_i = i$, and generate grid labels $p_i(g_i, 0, 1, 0, 0, i)$ for each entrance and exit, and add p_i to both set P and set R simultaneously.

3.2 Search for accessible walking distance

Starting from the walking grid at each entrance and exit of the urban rail transit station, the algorithm traverses and searches the accessible walking distance within a given time or distance threshold. The algorithm flow is shown in Fig. 5, and the search steps are as follows.

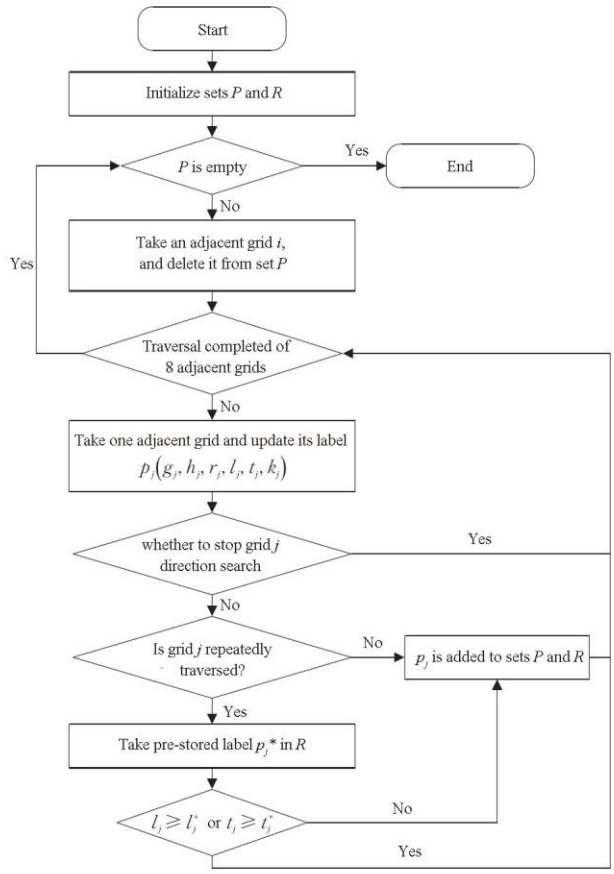

Fig. 5 Algorithm flowchart for calculating accessible walking distance of urban rail transit stations based on walking grids

1) Whether set P is empty is determined. If it is, the iteration terminates. If not, we select a grid i from P and remove it from the set P. Based on the code g_i of grid i, codes g_j of the 8 adjacent grids j are calculated, where j = 1, 2, 3, ..., 8.

2) Whether all 8 adjacent grids have been traversed is determined. If so, we return to step 1). If not, we select one adjacent grid j and update the grid label $p_j(g_j, h_j, r_j, l_j, t_j, k_j)$ (abbreviated as p_j) according to the following specific rules:

(1) We update the rules for h_j and r_j. Whether set S contains the grid with the number g_j is determined. If not, we set the default values $h_j = 0$ and $r_j = 1.0$. If it does, we retrieve the elevation value h_j and the walking speed reduction factor r_j from the label $s_j(g_j, h_j, r_j)$. If the elevation value $h_j = \pm1$, it indicates that the grid is located in the interchange overlap area and the grid elevation needs to be further determined dynamically based on the walking path. If $h_j = +1$, it indicates that the grid is reached by walking from the upper level to the overlap area, and $h_j = +1$ is set. If $h_j = -1$, it indicates that the grid is reached by walking from the lower level to the overlap area, and $h_j = -1$ is set.

(2) We update rules for l_j, t_j, and k_j. $l_j = l_i + \Delta_i$, $t_j = t_i + \Delta_i/(vr_j)$, $k_j = k_i$, where Δ_i is the grid step length, in m, and v is the walking speed on the projection plane, in m·s^{-1}. If j is located directly east or west of i, Δ_i takes the length of the horizontal grid edge, in m; if j is located directly south or north of i, Δ_i takes the length of the vertical grid edge, in m; if j is located in the northeast, northwest, southeast, or southwest of i, Δ_i takes the length of the diagonal grid line, in m.

3) We determine whether to stop searching in the direction of adjacent grid j. If so, we return to step 2); otherwise, we proceed to step 4). The judgment criteria are as follows:

If $g_j \notin W$, it indicates that grid j has exceeded the walking space range, and the search in the direction of grid j is stopped;

If $|h_j - h_i| > 1$, it indicates that grids j and i are located in disconnected upper and lower elevation layers, and the search in the direction of grid j is stopped;

If $l_j > l_{max}$ or $t_j > t_{max}$, it indicates that the distance or time for grid j to walk to the entrance/exit of the urban rail transit station exceeds the threshold, and the search in the direction of grid j is stopped.

4) Whether the adjacent grid j has been traversed repeatedly is determined. If the grid with the number g_j is not included in the set R, it indicates that grid j is traversed for the first time. We add the label p_j to both sets P and R simultaneously, and return to step 2). If the grid with the number g_j is included in the set R, it indicates that grid j has been traversed previously. We record the pre-stored label $p_j^*(g_j, h_j^*, r_j^*, l_j^*, t_j^*, k_j^*)$ (abbreviated as p_j^*) for j in the set R. If $l_j \geq l_j^*$ or $t_j \geq t_j^*$, we stop searching in the direction of the adjacent grid j and directly return to step 2); if $l_j < l_j^*$ or $t_j < t_j^*$, we delete p_j^* from the set R, add the label p_j to both sets P and R simultaneously, and return to step 2).

After the traversal is completed, the area covered by the grids in set R is the accessible walking distance. Based on the grid labels, the walking distance, walking time, and the number of the nearest entrance/exit to the urban rail transit station can be obtained.

4 Case application

4.1 Current case assessment

The Ranjiaba Station of Chongqing Metro was taken as an example for the current status assessment. This station is an underground station with three lines passing through, namely, Line 6, Line 5, and the Ring Line, with a total of eight entrances and exits. A walking surface centered around the station with a radius of approximately 1.2 km was constructed. Special areas such as overpasses, walking bridges and underpasses, and signal-controlled intersections for pedestrian crossing were mapped onto the walking surface, and walking speed reduction factors and elevation labels were set. The grids were divided according to the size of 0.1” × 0.1” (longitude difference × latitude difference), and the grids were encoded. Grid search was carried out starting from the eight entrances and exits. After traversing, the walking distance and time from each grid to the nearest entrance or exit were obtained. The walking distance and time within 5 min and 10 min of the Ranjiaba Station are shown in Fig. 6a.

Ignoring the internal walking distance (time) within the plots surrounding the station, the walking distance (time) from the grid where the plot opening is located to the nearest station entrance/exit was used to assign values to the plot attributes. When there are multiple openings in a plot, the opening closest to the station is selected; when the plot is fully open, the point on the plot boundary closest to the station is taken as the opening. The distribution of walking time from the plots surrounding the Ranjiaba Station to the station is shown in Fig. 6b.

We used the buffer zone analysis method and took an 800 m radius buffer zone as the accessible walking distance, resulting in a land area of 203 hm^2 covered by the station. According to the grid search algorithm proposed in this article, with a time threshold of 10 min, the land area covered by the station was 148 hm^2, which is about 73% of the result calculated by the buffer zone analysis method. The calculation result of the buffer zone analysis method was significantly larger than the actual service range of urban rail transit stations, which may result in overestimated passenger flow forecast values or other indicators. Thirty-three plots surrounding the station were selected to investigate the time required to walk from the entrance of each plot to the entrances and exits of the nearest station, and the results were compared with the calculation results of the grid search algorithm. The results showed that the average error between the measured results and the calculated results was 24 s, with a relative error of 10%, indicating that the method proposed in this article can accurately analyze the true accessible walking distance of the station.

An assessment was conducted on 240 existing urban rail transit stations in Chongqing as of the end of 2022. Based on the buffer zone analysis method, it was found that the proportion of land within an 800 m radius buffer was 29.2% (ideal value). However, according to the grid search algorithm proposed in this article, the proportion of land within a 10-min real walking distance from urban rail transit stations was 20.1% (approximately 69% of the ideal value), and the population proportion was 40.5%. The analysis results indicate that due to the adverse conditions of the mountainous terrain, the service coverage of Chongqing's urban rail transit system is significantly lower than the ideal value, resulting in a lower passenger intensity of urban rail transit. It suggests that optimizing and improving the walking connection system around stations not only has great potential but also is an effective means of revitalizing urban rail transit assets and maximizing investment benefits.

4.2 Planning case evaluation

Based on the grid search algorithm proposed in this article, various planning schemes, such as increasing the number of entrances and exits of urban rail transit stations, adjusting the layout of entrances and exits, adjusting the layout of plot openings, opening enclosed residential areas, and adding dedicated walking pathways, can be evaluated for their effectiveness. Taking Liujiaping Station on Chongqing Metro Line 6 as an example, the large residential area to the north of the station has a long detour distance to the station by walking. Therefore, it is planned to add a walking bridge crossing a water body and a walking ramp to overcome elevation differences within the northern park (see Fig. 7). The evaluation results show that after the implementation of the scheme, the walking distance from the northern residential area to the station is shortened by more than 1 000 m, saving about 10 min in the walking time, and benefiting approximately 8 000 residents.

a Walking isotime circle centered around the station

b Walking time distribution from the surrounding plot to station

Fig. 6 Walking distance accessibility range of the Ranjiaba Subway Station in Chongqing

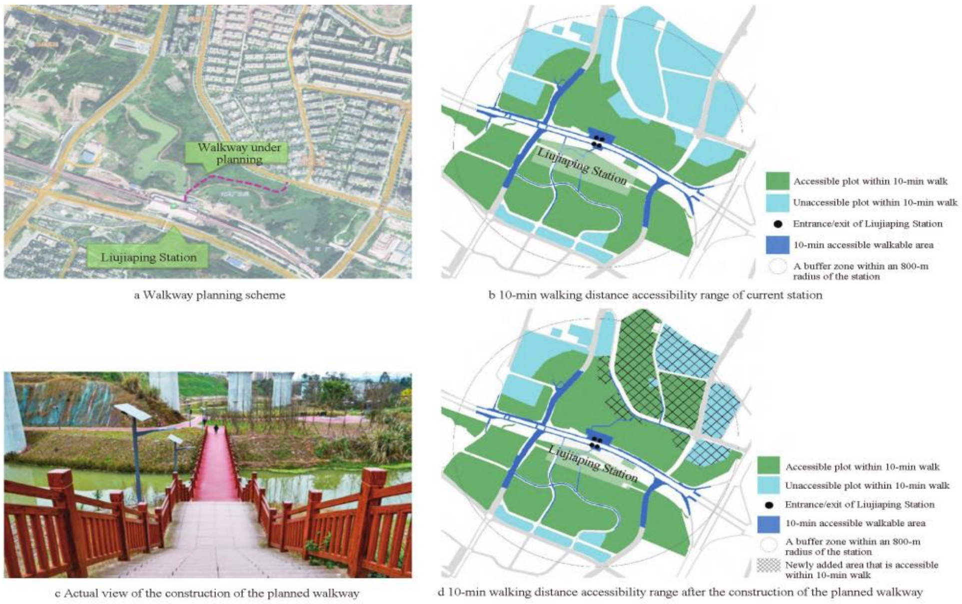

Fig. 7 Evaluation of the walkway planning scheme for the Liujiaping Subway Station in Chongqing

4.3 Application discussion

The evaluation method for the accessible walking distance proposed in this article can be extended to calculate the service range and competitive advantage area of public service facilities such as bus stops, community hospitals, primary schools, kindergartens, and supermarkets. We can simply replace the entrances and exits of urban rail transit stations with the openings of various public service facility plots, and set different time thresholds (such as 5 min, 10 min, 15 min) according to the service requirements of the facilities, then the true accessible walking distance of the service facilities can be obtained, thus evaluating the construction effectiveness of the “15-min living circle” [21–22], which refers to the opportunities for residents to access urban functions such as living, working, shopping, education, healthcare, and entertainment within a 15-min walking distance. If multiple service facilities of the same type are input, there may be situations where the walking grid is simultaneously served by multiple adjacent facilities. In this case, the grid is attributed to the facility with the closest walking distance, thus outputting the competitive advantage ranges of multiple facilities.

5 Conclusion

This paper proposed a method for accurately calculating the accessible walking distance of urban rail transit stations based on walking grids. Different from buffer zone analysis and network analysis, this method comprehensively considered the impacts of terrain elevation differences, road slopes, and street crossing facilities, and can better simulate the implementation effect of spacious walking spaces such as parks, squares, and open residential areas. It can be used for both the assessment of the current built environment and the testing and evaluation of planning scenarios, and can be extended to the assessment of various public service facilities beyond urban rail transit.

This article divided the grid based on 0.1” × 0.1” (longitude difference × latitude difference), with a single grid size (in the area of 30°N latitude) of approximately 2.68 m × 3.09 m, which can basically meet the accuracy requirements for block-scale analysis. If there are more refined analysis requirements, the grid size can be reduced and the grid coding can be modified, but the grid search computation will increase exponentially. Conversely, the grid size can be expanded to reduce the grid search computation.

The results of the case analysis indicate that due to the influence of the mountainous terrain, arterial roads, or residential area barriers, the actual service range of urban rail transit stations in Chongqing is only 69% of the ideal value, which is significantly lower than the ideal range. In the next step, based on accurate accessible walking distance calculations, efforts can be made to optimize urban rail transit passenger flow forecasting, urban rail transit network coverage population and land use assessment, integrated comprehensive development scope delineation of stations, and walking system planning and design around stations, thus improving the accuracy of analysis.

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