Estimating walking access area for rail transit station based on discrete choice model

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Abstract: The discrete choice model is used to estimate the walking access area of rail transit stations while considering the influence of existing competition from other traffic modes. The acceptable walking access area is determined according to the willingness of passengers to walk who prefer rail transit compared with bus and automobile. Empirical studies were conducted using the survey data of six stations from the rail transit in Nanjing, China. The results indicate that the rail transit is more preferable compared with bus and private automobile in this case when excluding the influence of individual and environmental factors. It is found that passengers tend to underestimate their willingness to walk. The acceptable walking access area of every rail transit station is different from each other. Suburban stations generally have a larger walking access area than downtown stations. In addition, a better walking environment and a scarcer surrounding traffic environment can also lead to a larger walking area. The model was confirmed to be effective and reasonable according to the model validation. This study can be of benefit to the passenger transportation demand estimation in the location planning and evaluation of rail transit stations.

Key words: walking access area; urban rail transit; discrete choice model; walking environment; competing traffic modes; passenger transportation demand

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With the process of urbanization, urban traffic is growing rapidly. High-capacity public transportation has become the major mode of transportation in many large cities, and is critical to the sustainability of urban transportation systems. Rail transportation has advantages over other public transport systems due to its high speed, low pollution, safety, punctuality and comfort, and has become more and more important in large cities around the world[1].

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A rail station has its walking service area, and we define the walking access distance as the straight-line distance beyond that most travelers (usually 75% to 90%) are not willing to walk from a trip origination to a rail transit station, which in turn defines the walking access area. This distance can reflect the direct influence of the rail station on travelers in this area. Service areas can be used to help understand the existing demand and determine the proportion of the population using the service at the station. Since this access area reflects the ability of the station to attract travelers, developing a model for walking access area is an effective way to evaluate the location of rail transit stations in rail transit planning, to predict the response of residents for future rail transit station arrangements, and to help analyze the surrounding walking environment of existing stations for future improvements.

According to Ref. [2], walk is the dominant mode for passengers to access public transport, which counts for 89% of bus trips from home and for about half of train trips from home in Sydney. Studies on rail transit access have been focused on the connections between trains, buses, cars and bicycles. Nevertheless, there still were several studies on walking access areas that dealt with the accessibility of rail sites, the influence of the surrounding environment on travelers' travel choice, the improvement of pedestrian connections, and the determination of the walking access area.

Previous studies have found that there is a significant difference between the walking distances of stops of various public traffic modes. A commonly acceptable walkable buffer for bus stops is one quarter-mile (400 m)[3-4]. While for metro stations, a half-mile (800 m) buffer is generally used[5]. However, these two rules of thumb are not consistently optimum in all circumstances due to the great diversity of regional characteristics, such as political, economic, geographic and socio-cultural environments, transit facilities and consumption habits[2, 6-12]. In the previous research of O'Sullivan and Morrall[13], they obtained a larger average walking distance for light-rail stations in the suburban than in the central business district (649 m compared with 326 m). Similarly, different average walking distances for rail transit stations were reported in Ref. [2] (803 m), Ref. [8] (565 m), Ref. [9]

(420 m) and Ref. [14] (928 m). The walking distances stated by respondents usually are inconsistent with the physical walking distances, since many respondents often reported their walking distances inaccurately[14]. Vale and Pereira[15] noted that short physical distances tend to be over-estimated and long physical distances tend to be under-estimated, but respondents perceive travel time much better than travel distance[16-18]. Thus, converting reported walking time to walking distance with a fixed walking speed can be more precise than asking respondents to estimate the distances directly.

Surveys on the influence factors of distance in which passengers are willing to walk to transit stops and stations can be found in a number of studies. Walking environment improvement (e. g., easing barriers, widened sidewalks, off-street pathways, providing parking spaces at the station, safety, multiple transit lines at a stop or station, shorter waiting time and an attractive and reliable transit service) along the way to the station could be the best approach to increase transit ridership and service areas[11-14, 19-21]. The features of the built environment and individual characteristics are also important factors influencing walking trips[10]. The individual characteristics mainly include household incomes, gender, age, education, vehicles in the household and trip purpose[2, 5, 8, 10, 14].

In previous studies, the recommended values for the walking access area of rail transit stations vary significantly, and the factors considered to obtain such values also vary. Since the average travel time is closely related to the walking environment and individual characteristics, most studies investigated the relationship between the walking distances and the influence factors, for instance, it is a linear regression observed by El-Geneidy et al[8]. However, previous researchers usually took the acceptable walking distance as the common standard measure (800 m) or an empirical percentile (e.g., 85%) of walking distances stated by respondents, which is easily subjectively misestimated as mentioned above. Besides, they did not consider the change in the willingness that passengers prefer the rail transit while there is a competition from other traffic modes.

In this paper, we use a discrete choice model to identify the walking access area for transit stations taking account of the traffic environment around transit stations and other competitive traffic modes. The acceptable walking time is not obtained directly from the statistical survey data, but calculated according to the traffic mode choice behavior of residents.

1 Analysis of the Factors Affecting Walking Access Area

The size of the walking access area is reflected by the mode choices of travelers. The farther the station is away from residents who choose to take the rail transit, the larger the walking access area. Before establishing a model, the factors affecting the walking access area should be analyzed. Based on the findings[22-25], these factors are summarized in this study as individual attributes and objective factors including the walking environment, travel time, travel costs, travel comfort factors(see Fig. 1).

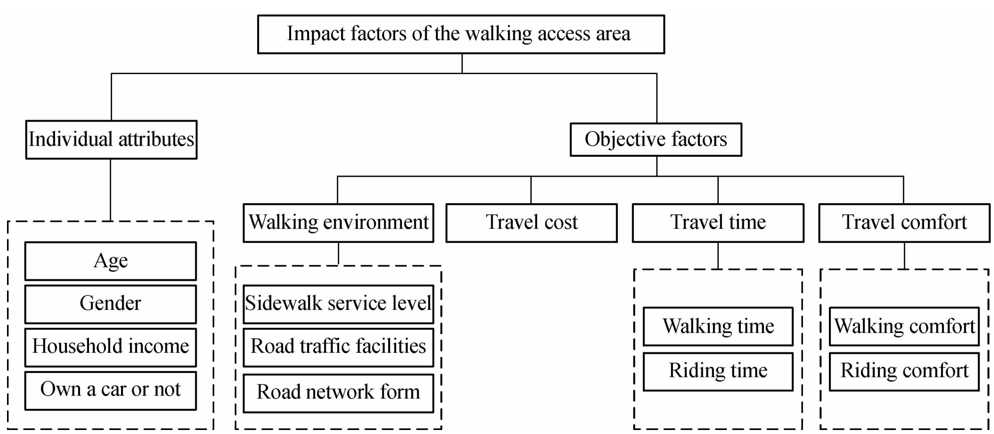


Fig. 1 Impact factors of walking access area

1.1 Individual attributes

Transportation mode choice is closely linked to individual attributes. Personal characteristics of residents in different regions are different, and there are also large discrepancies in peoples' preferences for travel modes, so the characteristics of populations must be analyzed first to study the walking access area. The main factors of personal characteristics considered include age, gender, household income, and car ownership.

1.2 Walking environment factors

1.2.1 Road network patterns

Due to the irregularity and complexity of the road network, a conversion factor is needed to derive the walking distance (radius) R that is used to define the access area. The actual distance for travelers to walk to the station is usually larger than the straight-line distance, and there is a convergent conversion factor Z between the two types of distances[14]. Generally, the road network around rail transit stations takes the form of a grid layout with or without diagonal links. For the grid road network with no diagonal links, all points within the distance of L from the station are located in a square of which the area is $2L^2$, as shown in Fig. 2(a). This is equivalent to a circle with a radius of

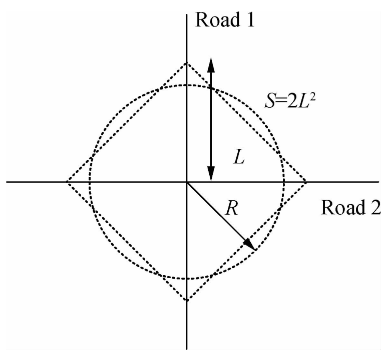
$$R = \sqrt{2/\pi}L \approx 0.798L \tag{1}$$

A distance of approximately $0.798L$ from both sides of line is a reasonable attraction range of the station, that is, the conversion factor $Z = 0.798$.

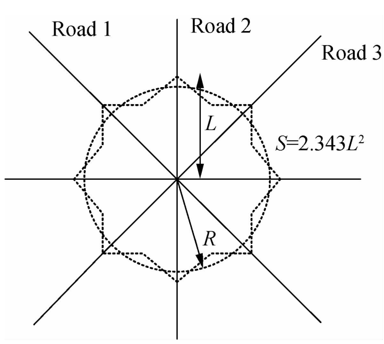
For a grid road network with diagonal links, as shown in Fig. 2(b), all points within the distance of L from the station are within an area of $8 - 4\sqrt{2}L^2 \approx 2.343L^2$, and this is equivalent to a circle with radius

$$R = \sqrt{2.343/\pi}L \approx 0.864L \tag{2}$$

In this case, the conversion factor $Z = 0.864$.



(a)



(b)

Fig. 2 Forms of grid street network. (a) Grid street network without diagonal links; (b) Grid street network with diagonal links

1.2.2 Sidewalk service level

There are significant differences in the sidewalk traffic conditions with the increase in urban traffic volume. In other words, the traffic situation can be evaluated by the sidewalk service level, and the evaluation mainly considers factors that affect pedestrian comfort and safety. The road traffic condition has a large impact on the access area of a rail station. Good infrastructure and service levels can give travelers a sense of security and comfort, and the rail transit station will in turn have a large service area. This is a benign cycle: Travelers enjoy the efficiency and comfort of rail transit, and the attraction of this transportation system is further enhanced. In China, the research on sidewalk service level primarily follows that of vehicle traffic. Based on the pedestrian traffic flow characteristics, shared space and pedestrian walkways are used to reflect the change of the pedestrian congestion and the freedom to walk. The pedestrian service level study should consider the cross-section design of the streets, operating characteristics of the pedestrian traffic flow, characteristics of vehicles, non-motorized transport units such as bicycles, barriers on the sidewalks, and the number and frequency of access points.

The locations of entrances and exits of the sidewalk are also important, because they affect both travel safety and comfort. Based on environmental design theories, a grid street pattern with well-connected pedestrian linkages and a small enclosure scale is expected to be positively associated with good walkability[26]. Whereas, ascending steps and traffic conflicts around stations reduce the willingness to walk[20]. Generally, the walking environments tend to present more “friendliness”, which denotes the presence of sidewalk, width of sidewalk, paved sidewalk, street crossing rating and transit amenities rating, in sections that are closer to the central business district and in older regions of the city[12].

1.2.3 Roadside facilities

Within a certain time period after a rail transit system starts operating, travelers may not be familiar with the rail station locations, particularly due to the fact that the rail stations are generally located underground. Especially in rural areas, travelers may spend much time looking for the rail station, and this may adversely impact the ridership of the rail transit. Therefore, clear roadside signs should be provided for the travelers.

Moreover, the quality of landscape, and layout and style of the buildings along the walking path also have effects on the psychology of pedestrians. Good lighting conditions can provide greater convenience and a sense of safety at night. These factors mentioned also strongly influence walking time.

1.3 Walking time and other factors

When traveling, travelers usually take into account factors such as time, cost, comfort, and convenience. For pedestrians, walking time is directly related at the access to rail transit, and walking comfort is also related to the walking environment at the station. For other modes, travel time may include transit time and waiting time. In addition, weather factors such as heat, humidity, and precipitation should be taken into consideration. However, these factors are seasonal and can affect all modes. In this paper, in order to minimize the effects of weather conditions, data collection was carried out on non-rainy days in November when the average temperature is about 12 ℃ and the climate is comfortable for walking.

2 Walking Access Area Model

2.1 Theoretical background of logit model

The logit model has been widely applied in the field of transportation in recent years[27-28]. It is applicable to the quantitative analysis of individual choice. The foundation for all logit models is the utility maximization theory, i. e., an individual will always make the choice achieve the overall utility maximization.

If U_{in} is the utility when individual n selects choice i and C_n is the choice set of the individual n, the individual n will choose i when $U_{in} > U_{jn}$ and $\forall j \neq i \in C_n$. According to the random utility theory, U_{in} can be defined as

$$U_{in} = V_{in} + \varepsilon_{in} \tag{3}$$

where V_{in} is the fixed term of the individual utility; ε_{in} is a stochastic term of the utility caused by unobserved elements.

The probability for individual n to select choice i, P_{in}, can be written as

$$P_{in} = \frac{\exp(V_{in})}{\sum_{j \in C_n} \exp(V_{jn})} \tag{4}$$

2.2 Walking access area model

Considering the urban trips of mid-to-long distance, there are three mode choices (rail transit, bus, car), and the origin and destination stations of rail transit and bus both involve walking. It is also assumed that only a single mode is used when a trip is made using public transportation. The utility function is then defined as

$$V_{in} = \sum_{k=1}^{K} \theta_{ik} X_{ink} \tag{5}$$

where X_{ink} is the k-th characteristic variable of selecting mode i for individual n; θ_{ik} is the coefficient value of the k-th variable in mode i.

Selecting the characteristic variables based on the influence factors of the walking access area is the next step. Based on the previous analysis of factors affecting walking access area, the characteristic variables for the walking access area model are shown in Tab. 1.

Tab. 1 Selection of the characteristic variables

Mode	Inherent dummy	Walking time	Riding time	Sidewalk service level	Travel cost	Comfort	Age	Gender	Household income	Car ownership
Rail transit	θ_1	X_{1n3}	X_{1n4}	X_{1n5}	X_{1n6}	X_{1n7}	X_{n8}	0	0	0
Bus	θ_2	X_{2n3}	X_{2n4}	X_{2n5}	X_{2n6}	X_{2n7}	0	X_{n9}	0	0
Car	0	0	X_{3n4}	0	X_{3n6}	X_{3n7}	0	0	X_{n10}	X_{n11}
Unknown coefficients	1	θ_3	θ_4	θ_5	θ_6	θ_7	θ_8	θ_9	θ_{10}	θ_{11}

The model coefficients are estimated using the maximum likelihood method. The maximum likelihood function is defined as

$$L = \ln \prod_{n=1}^{N} \prod_{i \in (1,2,3)} P_{in}^{\delta_{in}} \sum_{n=1}^{N} \sum_{i \in (1,2,3)} \delta_{in} \ln(P_{in}) \tag{6}$$

where

$$\delta_{in} = \begin{cases} 1 & \text{Individual } n \text{ chose } i \\ 0 & \text{Individual } n \text{ did not choose } i \end{cases}$$

Only those significant variables are kept in the model. The significance of the variables is investigated by conducting t-tests. If t value of θ_i is greater than 1.65, it is considered that the variable i selected for the model is significant at the significance level of 90%.

After the values of the coefficients are obtained, the travel utility functions of the rail transit, bus and car are written as

$$\left.\begin{aligned} V_{\text{rail}} &= \theta_1 + \theta_3 X_{1n3} + \theta_4 X_{1n4} + \theta_5 X_{1n5} + \theta_6 X_{1n6} + \theta_7 X_{1n7} + \cdots \\ V_{\text{bus}} &= \theta_2 + \theta_3 X_{2n3} + \theta_4 X_{2n4} + \theta_5 X_{2n5} + \theta_6 X_{2n6} + \theta_7 X_{2n7} + \cdots \\ V_{\text{auto}} &= \theta_4 X_{3n3} + \theta_6 X_{3n6} + \theta_7 X_{3n7} + \cdots \end{aligned}\right\} \tag{7}$$

As mentioned above, the attraction of rail transit is superior compared with that of bus. Besides, in China, due to the bad traffic environment in urban surface areas, it is quite difficult for automobile drivers to reach the free-flow speeds. A statistic average car travel speed is 33.72 in the city of Beijing[29], while the average travel speed for urban rail transit is 30 to 40 km/h reported by Li[30]. In other words, the rail transit is the most rapid traffic mode in general, especially during rush hour. Therefore, it can be supposed that V_{rail} is, in most cases, larger than V_{bus} and V_{auto} when $X_{1n3} = 0$. Evidently, the closer the travelers are to the station, the more efficient the rail transit, which means that the value of V_{vail} decreases with the increasing walking time, X_{1n3}. Thus, we can consider that the access area of a station approaches the boundary when the utility of rail transit is equal to the maximum value in utilities of the bus and car, that is, when $V_{\text{rail}} = \max(V_{\text{bus}}, V_{\text{auto}})$. The longest accepted walking time X'_{1n3} for a rail station can then be derived.

According to the longest accepted walking time, considering the network shape around the rail station, walking access distance R can be calculated as

$$R = SX'_{1n3}Z \tag{8}$$

where S is the pedestrian walking speed, typically with a value of 4 km/h; Z is the conversion factor calculated using Eqs. (1) or (2) based on the shape of the network.

3 Study Data

This paper mainly studies the impact of the walking access area based on trip characteristics. Considering that the travel time values may be different between downtown residents and suburban residents, three typical suburban station sites and three typical downtown station sites are selected in this study according to the position and neighboring environment of station (see Fig. 3). Surveys were conducted for areas around the entrances of these stations in November, 2010. The conducted surveys included the passenger behavior survey and the walking environment survey. Meanwhile, a residents' opinion survey was also carried out mainly to investigate the maximum acceptable walking time. The primary survey objects were the residents in the residential areas surrounding these stations, and the surveys focused on the personal characteristics of residents and walking environmental characteristics. The number of valid samples and that of those respondents who are rail users are shown in Tab. 2. In many cities, for example, Sydney, the guidelines recommend that suitable walking area should be provided to 90% of the regional population, so the 90th percentile is selected to identify the acceptable walking time[31-32].

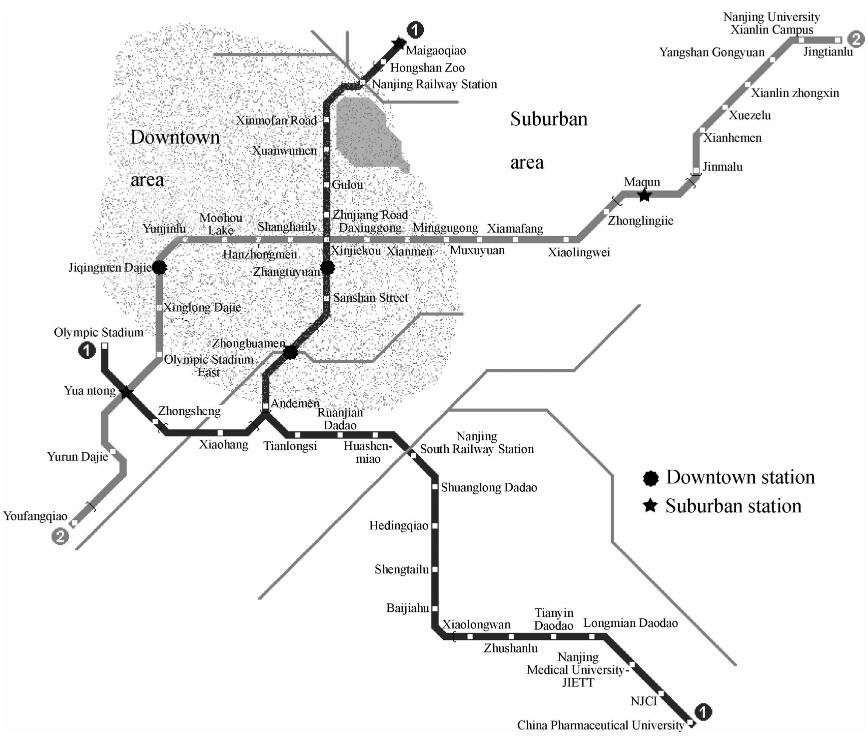


Fig. 3 Location of surveyed stations in Nanjing

Tab. 2 Nanjing rail site investigations

Investigation site	Suburban stations			Downtown stations		
	Maigaoqiao	Yuantong	Maqun	Zhangfuyuan	Zhonghuamen	Jiqingmen Street
Number of residents surveyed	348	341	336	337	331	342
Number of rail users	162	213	185	164	173	159

4 Model Implementation and Discussion

4.1 Model calibration and results

The coefficients of the multinomial logit (MNL) models were estimated using the maximum likelihood method. The resulting coefficients after removing the gender variable, which turn out to be insignificant, are shown in Tab. 3 and Tab. 4.

The results show that the t-test value of each parameter is significant at 90% significance level. The coefficient values are substituted into Eq. (8), and the transportation utility functions are determined. Using the walking time as an unknown quantity and maintaining the values of the other characteristic variables constant, the acceptable maximum walking time for each resident of the survey site is determined based on the assumption of equal utility values. Afterwards, using the maximum walking time that 90% residents think acceptable, the walking access distance is calculated using Eq. (9). The maximum acceptable walking time and walking access distance of each station are shown in Tab. 5.

Tab. 3 Results of parameters and t values (suburban sites)

Suburban site	Variable	Inherent dummy θ_1	Inherent dummy θ_2	Walking time θ_3	Travel time θ_4	Walking service level θ_5	Travel cost θ_6	Comfort θ_7	Age θ_8	Household income θ_{10}	Cars ownership θ_{11}
Maigaoqiao	Calibration value	16.29	2.10	−1.29	−0.76	0.54	−1.99	1.21	−2.00	2.77	5.76
	t value	3.76	4.21	2.85	−1.81	1.66	2.33	−1.7	2.01	1.88	4.06
Yuantong	Calibration value	15.24	3.10	−1.28	−0.839	0.963	−1.53	1.18	−1.93	2.56	4.96
	t value	3.42	3.98	2.76	−1.73	1.58	2.14	−1.73	2.11	1.87	4.12
Maqun	Calibration value	15.64	2.53	−1.31	−0.96	0.63	−2.10	1.17	−2.04	2.48	4.15
	t value	3.21	4.26	2.63	−1.74	1.58	2.47	−1.68	2.31	1.74	4.23

Tab. 4 Results of parameters and t values (downtown sites)

Downtown site	Variable	Inherent dummy θ_1	Inherent dummy θ_2	Walking time θ_3	Travel time θ_4	Walking service level θ_5	Travel cost θ_6	Comfort θ_7	Age θ_8	Household income θ_{10}	Cars ownership θ_{11}
Zhangfuyuan	Calibration value	14.93	1.96	−1.56	−0.58	0.69	−1.32	1.13	−1.98	2.90	5.89
	t value	3.44	3.85	2.79	−1.69	1.72	2.33	−1.69	2.15	1.73	4.37
Zhonghuamen	Calibration value	14.63	2.26	−1.43	−0.63	0.83	−1.20	1.02	−1.87	2.75	5.40
	t value	3.43	4.36	2.74	−1.93	1.63	2.47	−1.56	2.25	1.79	4.24
Jiqingmen street	Calibration value	15.11	3.21	−1.40	−0.74	0.75	−1.24	1.11	−1.94	2.83	5.89
	t value	3.85	3.86	2.54	−1.68	1.43	2.35	−1.69	2.32	1.76	4.37

Tab. 5 Walking access area of selected rail transit stations in Nanjing

Site	Suburban stations			Downtown stations		
	Maigaoqiao	Yuantong	Maqun	Zhangfuyuan	Zhonghuamen	Jiqingmen Street
Acceptable maximum walking time/min	18.1	16.9	17.5	14.8	14.3	15.1
Conversion coefficient	0.750	0.750	0.750	0.798	0.798	0.798
Walking access distance/m	904	844	874	787	760	803

4.2 Model validation and discussions

Survey data were used to validate the walking access area model. The differences between the survey values and model values for walking access distance are summarized in Tab. 6. It is clear that the walking access area of every rail transit station is different from each other. The walking access area is affected by trip characteristics including the walking environment and individual attributes of travelers. The survey results and model calculation results are in general very close and the relative difference is almost less than 6%, indicating that the model is valid and the resulting walking access area values are reasonable and reliable. In addition, for the six stations, the survey values are all less than the model values, which suggest that passengers may tend to underestimate their tolerance for walking time.

According to the parameters estimation in Tab. 3 and Tab. 4, the rail transit has larger inherent dummies than the other two modes, which means that the residents who live close to rail stations may be more inclined to choose rail transit when walking time and sidewalk service level are equal to zero and other factors are identical for all modes. Excluding the influence of other service factors,

Tab. 6 Difference of walking access distance between the developed model and stated preference survey

Site		Suburban stations			Downtown stations		
		Maigaoqiao	Yuantong	Maqun	Zhangfuyuan	Zhonghuamen	Jiqingmen Street
Walking access distance/m	Developed model	904	844	874	787	760	803
	Stated preference survey	880	800	826	744	721	754
Relative difference/%		2.7	5.2	5.5	5.5	5.1	6.1

e. g., travel time, travel cost, comfort, the diversity of acceptable walking times between the rail transit station and bus stop in the same section can be calculated as $(\theta_2 - \theta_1)/\theta_3$. Thus, rail transit stations present longer acceptable walking times than bus stops in both suburban and downtown districts (i. e., the average diversities of acceptable walking times in these two districts are 10. 18 and 8. 49 min, respectively), which also indicates that the rail transit stations are more competitive in suburban districts.

The modeling results of the walking access area of a suburban station is generally larger than that of a downtown station and the survey results confirm this conclusion, which reveals that the location and the surrounding environments of a rail transit station can directly affect its attraction area. In regard to the stations in downtown, there are people living/working crowded together in tall buildings near these stations. Downtown rail stations are usually closer together; and there are many competing bus routes and substantial taxis available. The worsened air quality caused by congested traffic in the area often reduces people's willingness to walk. People may need to walk around due to the inconvenient entrances and exits of rail transit in the downtown area. During rush hours, one can find that downtown stations are unpleasantly full of people inside, which leads to a reduction of the comfort and level of service. All these reasons may be explanations for a smaller access area for a downtown station as compared to a suburban station.

Stations in the same region may also have differences in their walking access areas due to the impacts of surrounding environment. For suburban stations, the walking environment around Maigaoqiao station is better than that around Yuantong Station and Maqun Station. For downtown stations, the surrounding walking facilities of Jiqingmen Street Station are better than those of Zhangfuyuan Station and Zhonghuamen Station. These suggest that better walking environments can lead to larger walking areas. This is also consistent with the results from the opinion survey.

The walking access area of Zhonghuamen Station is the smallest in the investigated stations. Actually, the traffic environment of Zhonghuamen Station is the most convenient in these six stations, which is just located on the inner ring road and where there are the most bus lines across the neighboring area. Furthermore, an inter-city bus station and an inter-city train station are situated not far from this station. In other words, the competing traffic modes, which mainly include bus and automobile, are easily available for passengers around this station. This indicates that the better traffic environment a transit station has, the shorter walking distance passengers are willing to accept.

5 Conclusions

1) This paper establishes a discrete choice model for transportation modal selection and proposes a method of using the mode choice model to estimate the walking access area. Compared with the traditional methods to determine the walking access area, the new method considers not only the influence of relevant factors but also the competition of other traffic modes, and the acceptable walking access area is determined by simulating the mode choice behavior of passengers.

2) The empirical results suggest that under the same condition, the rail transit presents the most attractive traffic mode when compared with bus and private automobile in this case, and the acceptable walking time of a rail transit station is more than twice that of bus stop. It is also found that the existing competing traffic modes can lead to a reduction in the walking access area of transit stations.

3) The size of walking access area reflects the ability of the station to attract travelers, and therefore the developed model and method can be used to evaluate and analyze the location of rail transit stations. The model can also be used to predict the response of residents to future rail transit station arrangements and provide a foundation for proper station location determination to facilitate the effective operations of the urban transit system and to help the sustainable development of a city.

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基于离散选择模型的城市轨道交通站点步行吸引范围估计

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摘要:采用离散选择模型对轨道交通车站步行吸引范围进行估计,当在某个距离下相比于公交和私家车乘客更愿意选择轨道交通出行时,认为该距离为乘客可接受步行范围.利用南京地铁 6 个站点的调查数据进行了实证研究.结果表明,在个人和环境因素相同的情况下轨道交通比公交车和私人汽车更具吸引力.研究还发现乘客往往会低估他们步行的意愿,对于不同的轨道交通车站可接受步行范围有所差异,其中郊区的车站通常比市区的车站具有更大的步行吸引范围.此外,良好的步行环境和较差的周边交通环境也会导致更大的步行吸引范围.检验结果表明该模型具有良好的有效性和合理性.该研究有助于轨道交通站点选址规划中的客流需求预测以及轨道交通站点的评价.

关键词:步行吸引范围;城市轨道交通;离散选择模型;步行环境;竞争交通方式;乘客交通需求
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