

IMPROVING TACTILE GROUND SURFACE INDICATORS BASED ON FUZZY-AHP METHOD: THE CASE OF GULOU DISTRICT, NANJING, CHINA

Mejoras en los indicadores táctiles de superficie con base en el proceso de jerarquía analítica difuso:
el caso del distrito de Nanjing, China

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ABSTRACT

There are many problems in the practical use of tactile ground surface indicators (TGSIs), and the large amount of TGSi construction currently being carried out does not always have a beneficial impact on the travel of visually impaired groups. Taking the roadside pedestrian space in the Gulou District of Nanjing City as an example, this paper established a TGSi quality evaluation system including six first-level indicators and 24 second-level indicators. The analytic hierarchy process (AHP) was used to determine the weight of the indicators at all levels, and evaluate six urban main roads, six urban secondary main roads and six sidewalks beside access roads, which were selected randomly. Visually impaired people were then asked to evaluate the TGSIs in the pedestrian spaces along these roads. Statistical analysis and evaluation showed that the indicators used in the evaluation system were satisfactory. The evaluation results revealed problems with the standardization, safety, accessibility, continuity, comfort and aesthetics of TGSIs in the urban roadside pedestrian space of Gulou. Analysis of the combined data showed that travel conditions for the visually impaired are currently worse in the old city area than in the new city area and that they are worse in low-grade pedestrian space than along high-grade roads. In order to solve these problems, strategies are put forward for improving the quality of TGSIs in the pedestrian space of Nanjing's Gulou District in four aspects: improving TGSi structure, optimizing TGSi location, improving the TGSi system, and adapting TGSi implementation according to local conditions.

Palabras clave: TGSi, vías urbanas, estado de evaluación, mejoramiento de la calidad

RESUMEN

Existen muchos problemas en el uso práctico de los indicadores táctiles de superficie (TGSIs, por sus siglas en inglés) y la gran cantidad de ellos que se están instalando no siempre tiene un impacto benéfico en el desplazamiento de los grupos con discapacidad visual. Considerando el espacio pedestre de la ciudad de Nanjing, distrito de Gulou, como

ejemplo, este trabajo establece un sistema de evaluación de la calidad de los TSGIs que incluye seis indicadores de primer nivel y 24 de segundo nivel. Se utilizó el proceso analítico jerárquico (AHP, por sus siglas en inglés) para determinar el peso de los indicadores en todos los niveles y para evaluar seis vías urbanas principales, seis secundarias y seis banquetas, además de vías de acceso, todas seleccionadas al azar. Se le pidió a personas con discapacidad visual que evaluaran los TSGIs en los espacios pedestres de las vías. La evaluación y el análisis estadístico mostraron que los indicadores utilizados en el sistema de evaluación fueron adecuados. La evaluación de los resultados reveló problemas con la estandarización, la seguridad, la accesibilidad, la continuidad, el confort y la estética de los TSGIs en los espacios pedestres de las vías urbanas en Gulou. El análisis de los datos combinados mostró que las condiciones de desplazamiento para las personas con discapacidad visual son peores en el área vieja de la ciudad que en la nueva, y también son peores en los espacios pedestres de las vías secundarias que en las primarias. Para resolver dichos problemas, se proponen estrategias para mejorar la calidad de los TSGIs en el espacio pedestre de Nanjing, distrito de Gulou, en cuatro aspectos: mejorar la estructura de los TSGIs, optimizar su localización, mejorar el sistema de TSGIs y adaptar la implementación de los TSGIs de acuerdo con las condiciones locales.

INTRODUCTION

As the most common barrier-free facility in the city environment, tactile ground surface indicators (TGSIs) play an important role in the daily travel of the visually impaired (Courtney and Chow 2000, Kobayashi et al. 2005, Dursin 2012). TGSIs were first developed in Japan (Courtney and Chow 2000b), but they were not initially broadly adopted there, and it was in the United States that the standardization of TGSIs began. China's large-scale promotion and construction of TGSIs originate from the policy promoting "national activities to create barrier-free cities." The length of urban roadside pedestrian space marked with TGSIs has become an important metric for urban civilization. However, through interviews with the visually impaired and on-site investigation of urban roadside pedestrian space TGSIs, it has been found that there are problems with TGSi implementation such as inconsistent planning, irregular construction, inadequate management, and design that is unsuited to the actual use process. Despite this, a search of the literature indicates that no research has been specifically targeted at evaluating the implementation of TGSIs in urban roadside pedestrian space. Scholars concerned about TGSIs have usually only proposed solutions to the problems found in TGSi investigations and have not used scientific logic to discriminate between the factors affecting the quality of TGSi implementation (Almeida et al. 2015, Aghaabbasi et al. 2018; Øvstedal et al. 2005, Kokusai 1977, Padzi et al. 2013, Mizuno et al. 2008, Da Silva et al. 2015, Pluijter et al. 2015). This study intends to select appropriate evaluation methods

and take Nanjing's Gulou District as an example to scientifically evaluate TGSi implementation in urban roadside pedestrian space.

The quality of the implementation of TGSIs in urban roadside pedestrian space is affected by many factors (Gitelman et al. 2019, Zhang et al. 2019), so its evaluation must be a multi-objective and multi-level process. The evaluation process involves a comprehensive consideration and comparison of the requirements of TGSi-related policy makers, planners, builders, and users, and of other related influencing factors (Totah, Menon, Jones-Hershinow, Barton, and Gates 2019). In addition to providing travel assistance for the visually impaired, TGSIs are also an important consideration in urban transportation planning. Some scholars have also discussed the impacts of connectivity, continuity, and topography of the sidewalk network on pedestrian safety, and the impact of roadside non-pedestrian space on the pedestrian environment of urban streets (Yi Kang et al. 2017). Although the entry points are different, these research results can provide support for the reliability of the research methods and influencing factors of this research. Some scholars collaborated with community residents in reviewing neighborhood facilities and proposed a method to evaluate neighborhood sidewalks using micro-scale factors.

Additionally, scholars have applied methods to improve the travel safety of the visually impaired as the construction of low-speed active safety systems for buses, and the use of wearable navigation devices (K. Hiroto and H. Katsumi. 2019). Vehicles and visually impaired persons are equipped with sensors to improve the response efficiency of the visually

impaired in the event of danger. At present, there is a lack of research on improving the safety of urban road pedestrian spaces through multi-dimensional reconstruction. From the existing literature, we learned that different professional fields place different emphasis on urban road pedestrian space TGSIs. For example, the transportation field pays more attention to the impact of traffic safety, the urban planning field concentrates more on the impact of space design, and computer science focuses on the use of sensors to improve the travel experience of the visually impaired. TGSIs are an important part of urban slow traffic planning. In research and practice, the method of combining slow traffic planning with TGSIs systems as the main factor of urban road traffic planning has not yet been seen. There is a lack of evaluation of TGSIs in urban road pedestrian spaces in combination with multiple participants, and a lack of research on designing strategies combined with evaluation indicators.

This study establishes a complete index system based on the influences exerted by these TGSi-relevant parties. The fuzzy evaluation method is employed to quantify the importance of the evaluation indexes and their sorting, calculated according to the importance of the index order rule layer derived from the weight of each index, which is determined based on survey results. This system is applied to the urban roadside pedestrian space TGSIs in Gulou District, and countermeasures are proposed based on the evaluation results.

These countermeasures fully consider the experience of relevant participants, including city managers, urban planners, and the visually impaired. The purpose of the countermeasures is to improve the spatial quality of TGSIs and provide index guidance in urban road pedestrian spaces. The main contributions of this work are as follows:

- 1) Through evaluation of the TGSi status of urban roadside pedestrian space in Nanjing's Gulou district, this paper analyzes TGSi implementation in different functional areas and different types within the road hierarchy, summarizes the common problems with, and characteristics of, urban roadside pedestrian space TGSIs in Gulou, and analyzes the reasons for these problems.
- 2) This paper proposes countermeasures to improve the current implementation of TGSIs in urban roadside pedestrian space in Gulou, from the perspectives of improving TGSi structure, making TGSi positioning more reasonable, perfecting the

TGSi system and setting it according to local conditions, and providing a reference for improving the quality of TGSIs in urban roadside pedestrian space.

- 3) A quality evaluation system for urban roadside pedestrian space TGSIs is established, providing a quantitative analysis method for studying the TGSIs of urban roadside pedestrian space in other areas.

Index and evaluation system construction

Method of developing the index system

The comprehensive evaluation of urban roadside pedestrian space TGSIs is a complex process, and both qualitative and quantitative indicators must be included in the evaluation index system, among which the qualitative indicators are more important. The analytic hierarchy process (AHP) is a multi-objective and multi-criteria decision analysis tool that enables the organization of subjective thought processes and is suitable to the requirements for a TGSi evaluation index system for urban roadside pedestrian space (Akkaya, Turanoğlu, and Öztaş 2015; Tyagi, Agrawal, Yang, and Ying 2017; Fan, Zhong, Yan, and Yue 2016). Therefore, AHP is selected as the method for determining an appropriate index system and weightings.

Factors influencing evaluation indexes

Owing to the small distance between the consideration of the different functions undertaken by different participants in this evaluation allows the factors influencing how urban roadside pedestrian space TGSIs are implemented to be divided into policy specification factors, planning and design factors, and the demands of the visually impaired (**Fig. 1**).

- 1) Policy norms. Policy factors include the urban barrier-free construction policies proposed by national, provincial and municipal government, and by barrier-free management units. The normative factors within this realm are the barrier-free design standards GB 50763-2012.
- 2) Planning and design factors. Planning factors include municipal facilities planning and TGSi line planning related to urban roadside pedestrian space. Design factors include the relationship between TGSi type and TGSi position, and the installation of TGSIs at nodes related to public facilities in the urban pedestrian space such as bus stations.

- 3) Demands of the visually impaired. The demands of the visually impaired for TGSIs in urban roadside pedestrian space constitute the main factor influencing the construction and evaluation of those TGSIs.

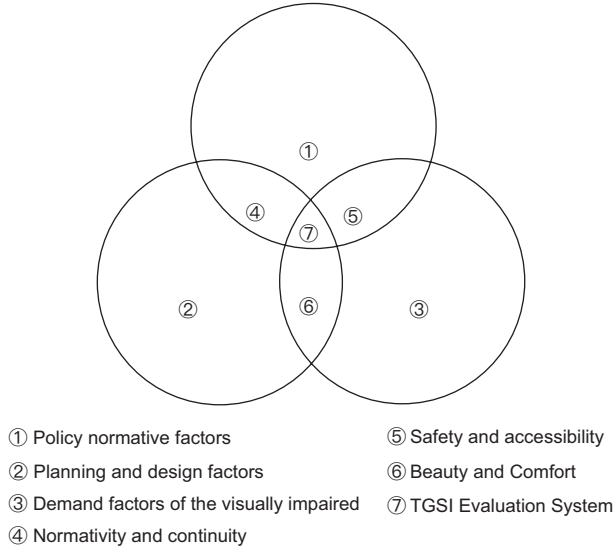


Fig. 1. The relationships between the factors influencing the evaluation system.

Survey process

This study undertook four surveys. The first is a basic survey of the status of the research object. The site surveyed 18 walking spaces on urban roads containing TGSIs, and randomly interviewed surrounding residents and the visually impaired. The first survey aimed to give an overview of the status of TGSIs in urban roadside pedestrian space by investigating the status of those in Nanjing. The characteristics, status, and demands of the visually impaired were investigated through interviews with groups of visually impaired people. The standards of barrier-free design were determined through investigation of policies, standards, and other relevant literature.

The second survey aimed to clarify and effectively evaluate the system by asking experts to fill out surveys, and through interviews with visually impaired people. The expert respondents were young architect committee members of the Jiangsu Architectural Society who participated in the design and demonstration of TGSIs in Gulou District, Nanjing, and the visually impaired group consisted of technicians at the Nanjing massage parlor for the blind. For more convenient calculation, 20 valid questionnaires were issued to both the experts and

the visually impaired, with an effectiveness rate of 83.33 %. If an evaluation factor was selected by less than 60 % of experts and visually impaired persons, the evaluation factor was judged to be invalid. The purpose of the third survey was to calculate the weight of the evaluation factors. In order to ensure that the weight results were scientifically robust, questionnaires were issued to the experts and the visually impaired respectively. In order to ensure the accuracy and fairness of the weighting conclusions, the weighting process combines interviews with visually impaired persons and experts. The final weight of the TGSIs evaluation was the weight redistributed according to a ratio of 6:4, by mathematically calculating the weight of each index.

The fourth round of research was to verify the evaluation of the current state of urban roadside pedestrian space TGSIs. This aspect of the research was conducted in 18 selected segments of urban roadside pedestrian space with TGSIs-demarcated pathways. The selection process is described in Section. Based on the evaluation index system, the locations where the questionnaires noted disrupted TGSIs space were visited. Then, a numerical control evaluation was calculated on the same semantic scale as used in the TGSIs quality evaluation results. These results were then compared with the survey results. The flow chart corresponding to the four surveys is shown in **figure 2**. This is due to the inconveniences and difficulty of travel experienced by the visually impaired. In order to improve efficiency, several sighted volunteers accompanied the visually impaired to complete related tasks.

Process of establishing the evaluation system

Establishing a hierarchical structure model of practical problems

The first step is to determine independent factors that affect TGSIs quality and combine these to form a complete indicator system.

Establishing a judgment matrix

Each index is calibrated according to the nine-level scale method, and the weights of elements at all levels relative to the overall objective are determined. This study used the geometric average method to determine the mean score of experts and visually impaired people when analyzing the criterion layer and index layer.

An AHP P2wise judgment matrix was constructed in the form of:

$$\text{Element set: } A = \{A_1, A_2, \dots, A_N\} \quad (1)$$

$$M \quad A_1 \quad A_2 \quad \cdots \quad A_N \quad (2)$$

$$V = \begin{Bmatrix} A_1 \\ A_2 \\ \vdots \\ A_N \end{Bmatrix} \begin{bmatrix} 1 & A_{12} & \cdots & A_{1N} \\ A_{21} & 1 & \cdots & A_{2N} \\ \vdots & \vdots & 1 & \vdots \\ A_{N1} & A_{N2} & \cdots & 1 \end{bmatrix} = (A_{ij})_{N \times N}, (A_{ij} = 1/A_{ji}) \quad (3)$$

where A is the set of evaluation indicators, M is the total evaluation index, V is each index layer, and the importance of the index element relative to itself is 1.

For each index layer in the evaluation index set $A_i = \{A_{i1}, A_{i2}, \cdots A_{ik}\}$ relative to the sub-index layer A_i , the relative importance judgment matrix for the indicator layers is obtained by pairwise comparison as follows:

$$A_i \quad A_{i1} \quad A_{i2} \quad \cdots \quad A_{ik} \quad (4)$$

$$W_i = \begin{Bmatrix} A_{i1} \\ A_{i2} \\ \vdots \\ A_{ik} \end{Bmatrix} \begin{bmatrix} 1 & a_{12}^i & \cdots & a_{1k}^i \\ a_{21}^i & 1 & \cdots & a_{2k}^i \\ \cdots & \cdots & \cdots & \cdots \\ a_{k1}^i & a_{k2}^i & \cdots & 1 \end{bmatrix} = a_{k \times k}^i, i=1,2,\cdots,m, (a_{ij}^i = 1/a_{ji}^i) \quad (5)$$

a_{ij}^i represents the discriminant value of the relative importance of elements A_{ii} to A_{ij} relative to A_i , and the significance sequences of each indicator can be determined by calculating the indicator layer element sequences.

Determining the relative weight of each index in the criterion layer and index layer

First, the significance sequences of each indicator are obtained according to the result of the judgment matrix, and the product root method is used to normalize the elements of the judgment matrix. The relative weights of the compared elements under a single criterion M and A_i are then obtained respectively.

- 1) The product square root method is used to calculate the geometric mean of the judgment matrix ($\bar{W}_i$)

$$\bar{W}_i = \left(\prod_{j=1}^n a_{ij} \right)^{\frac{1}{n}} \quad i,j=1,2,\dots,n \quad (6)$$

a_{ij} is the jth element in layer i in the relative importance judgment matrix of the original index layer, n is the number of indicators in each index layer under the criterion layer, and $\bar{W}_i$ is the geometric mean of layer i of the relative importance

judgment matrix of the original index layer.

- 2) The eigenvector is obtained by normalizing the geometric mean of each index:

$$W_i = \frac{\bar{W}_i}{\sum_{j=1}^n \bar{W}_j} \quad i,j=1,2,\dots,n \quad (7)$$

W_i represents the weight obtained for the indicator of the ith indicator layer in the relative importance judgment matrix of the original indicator layer. n represents the number of indicators in the original index layer, and $\bar{W}_i$ represents the geometric average value of the ith layer of the relative importance judgment matrix of the original index layer.

- 3) The maximum eigenvalue of the judgment matrix $\lambda_{\max}$ is then calculated:

$$\lambda_{\max} = \frac{1}{n} \sum_{i=1}^n \frac{(\sum_{j=1}^n a_{ij} W_j)}{W_i} \quad i,j=1,2,\dots,n \quad (8)$$

a_{ij} is the jth element in the relative importance judgment matrix of the original indicator layer, n is the number of indicators in each indicator layer under the criterion layer, and $\lambda_{\max}$ is the maximum eigenvalue of the judgment matrix of the research object.

- 4) The consistency index CI and consistency ratio CR are calculated

$$CI = \frac{\lambda_{\max} - n}{n - 1} \quad (9)$$

When the value of n is 2, the positive and negative results of the matrix are consistent, so it is not necessary to verify its consistency. When the value of n is greater than 2, the CR calculation matrix is used to judge whether the results are consistent. CR (consistency ratio) = CI (consistency index) / RI (random consistency), where the values for RI (random consistency) are as shown in **table I**.

TABLE I. AVERAGE RANDOM CONSISTENCY INDEX.

n	1	2	3	4	5	6	7	8	9	10
RI	0	0	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49

Calculating weight

The weight of all indexes in the indicator layer relative to the total target is

$$W = [W_1, W_2, \dots, W_N]^T \quad (10)$$

Index system construction

The factors affecting TGSi quality discussed in this research can be summarized into 24 indexes related to six aspects: standardization, security, accessibility, continuity, comfort, and aesthetic (**Fig. 2**)

Evaluating index weight

The factors affecting TGSi quality discussed in this research can be summarized into 24 indexes related to six aspects: standardization, security, accessibility, continuity, comfort, and aesthetic (**Fig. 2**). The indicator selection had gone through the first round, combined with field visits and interviews with visually impaired people. The final indicators are determined after selection by experts. This indicator system is the result of screening after a combination of multiple factors.

Evaluation of index weight

This study scientifically and comprehensively analyzes the weight coefficient of each TGSi evaluation index by determining and synthesizing the corresponding weight coefficients generated by surveys completed by both experts and visually impaired persons. Through the open-ended questionnaire survey of experts and people with visual impairment, we can identify several factors that appear to be the most significant.

The basis of the index weight of the expert questionnaire is as follows: a total of 43 expert rating questionnaires were issued, and 40 were collected. Excel was used to integrate them through the geometric mean method. Matlab was used to calculate the aggregation matrix of standardization, security, accessibility, continuity, comfort, aesthetic, and their second-level indicators, and the result was summarized.

The basis of the index weight of interviews with the visually impaired is: 44 visually impaired people were interviewed in this study, and 40 effective interviews were conducted. Among the participants, 21 had primary blindness, 16 had secondary blindness, and 3 had tertiary low vision. The importance of each indicator was evaluated and scored. The same method was used to calculate the aggregation matrices, and the combined weight of the results of each index was calculated to obtain the final weight coefficient of each index.

Final combined weight

Considering that TGSIs are a part of roadside pedestrian space and the perception of the TGSi

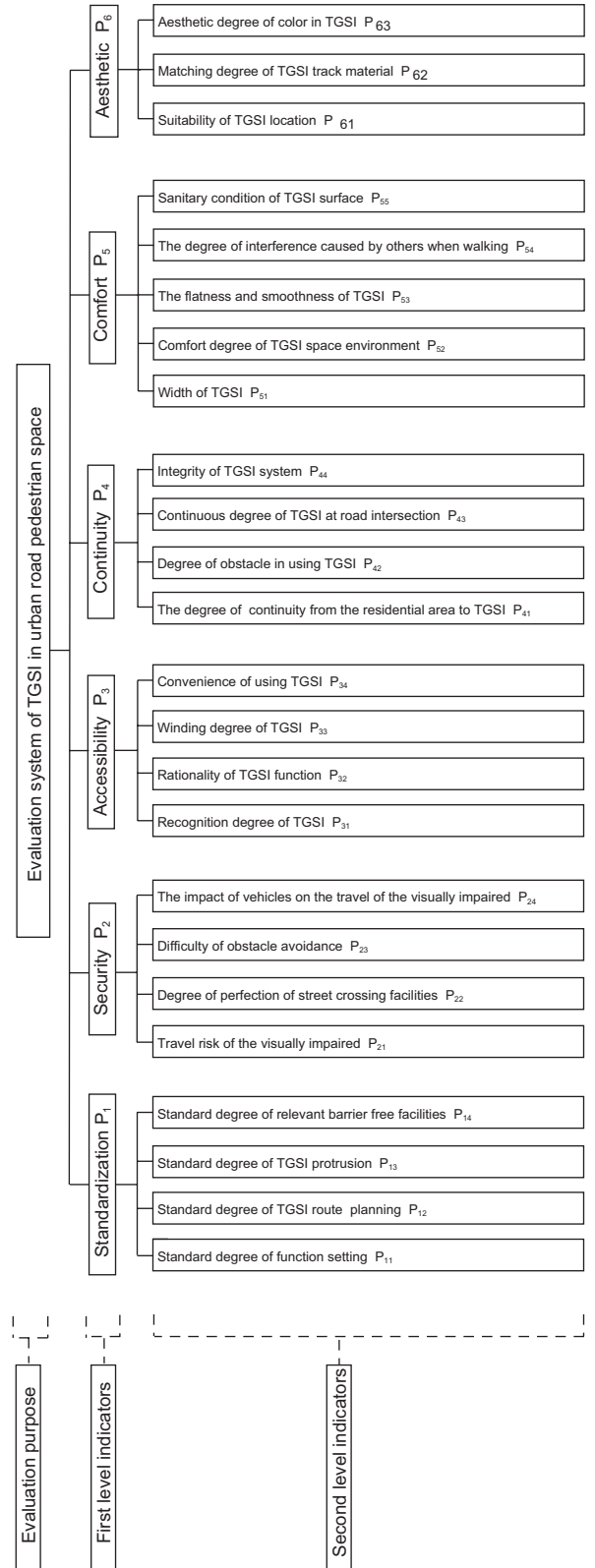


Fig. 2. Evaluation system of TGSIs in urban road pedestrian space

environment by visually impaired people plays an important role in their evaluation, the comprehensive evaluation results of the visually impaired and experts were combined at a ratio of 6:4 to arrive at the evaluation weight. The final integration results are shown in **Table II**.

Evaluation of system construction

This study applies the AHP and fuzzy comprehensive evaluation methods to evaluate the spatially varying quality of urban roadside pedestrian space TGSIs. This is achieved through the following steps (**Fig. 3**):

1) Establishing a set of evaluation elements

An evaluation element set was established, as this is the basis for ensuring effective quantification of an evaluation index. An evaluation set is the mathematical set expression for each index layer and criterion layer index, such as the first-level indicators element $P_i = \{P_{i1}, P_{i2}, \dots, P_{in}\}$ and

second-level indicators element $P_i = \{P_{i1}, P_{i2}, \dots, P_{in}\}$.

2) Establishing the evaluation set for TGSi quality

The evaluation set $V = \{V_1, V_2, \dots, V_n\}$ was established.

A semantic scale was defined to facilitate the comparison of evaluation results. There are five levels of this grade classification in this standard set: good, fine, ordinary, poor and bad. The corresponding semantic score is 5, 4, 3, 2, 1, and the corresponding evaluation result range (F) is $F > 4.5$ (good), $4.5 \geq F \geq 3.5$ (fine), $3.5 \geq F > 2.5$ (ordinary), $2.5 \geq F > 1.5$ (poor), $1.5 \geq F$ (bad).

3) Constructing a fuzzy evaluation matrix

The fuzzy matrix of single-factor evaluation according to the index and the evaluation set is $R = \{R_1, R_2, \dots, R_n\}$.

4) Multi-factor comprehensive evaluation based on the weight set

A fuzzy composition operator was used to process data and generate fuzzy evaluation vector E:

TABLE II. WEIGHT SUMMARY AND RANKING OF INDICATORS AT ALL LEVELS

First level Indicators	Combination Weight	Second Level Indicators	Group Combination Weight	Final Combination Weight	Sequences
Standardization P_1	0.28656	P_{11}	0.14438	0.0414	8
		P_{12}	0.15272	0.04364	6
		P_{13}	0.36272	0.10386	3
		P_{14}	0.34022	0.09762	4
Security P_2	0.43782	P_{21}	0.42022	0.18388	1
		P_{22}	0.38918	0.17044	2
		P_{23}	0.11604	0.05068	5
		P_{24}	0.0746	0.03282	10
Accessibility P_3	0.11496	P_{31}	0.3901	0.04512	9
		P_{32}	0.37964	0.04352	7
		P_{33}	0.10216	0.01178	18
		P_{34}	0.12816	0.01454	15
Continuity P_4	0.05024	P_{41}	0.09538	0.00478	23
		P_{42}	0.53314	0.0268	12
		P_{43}	0.06604	0.00332	24
		P_{44}	0.3055	0.01534	16
Comfort P_5	0.07726	P_{51}	0.09906	0.00762	19
		P_{52}	0.20056	0.01544	14
		P_{53}	0.42932	0.03316	11
		P_{54}	0.18666	0.01446	17
		P_{55}	0.08434	0.00648	20
Aesthetic P_6	0.03326	P_{61}	0.55984	0.01854	13
		P_{62}	0.21642	0.00722	22
		P_{63}	0.22374	0.0075	21

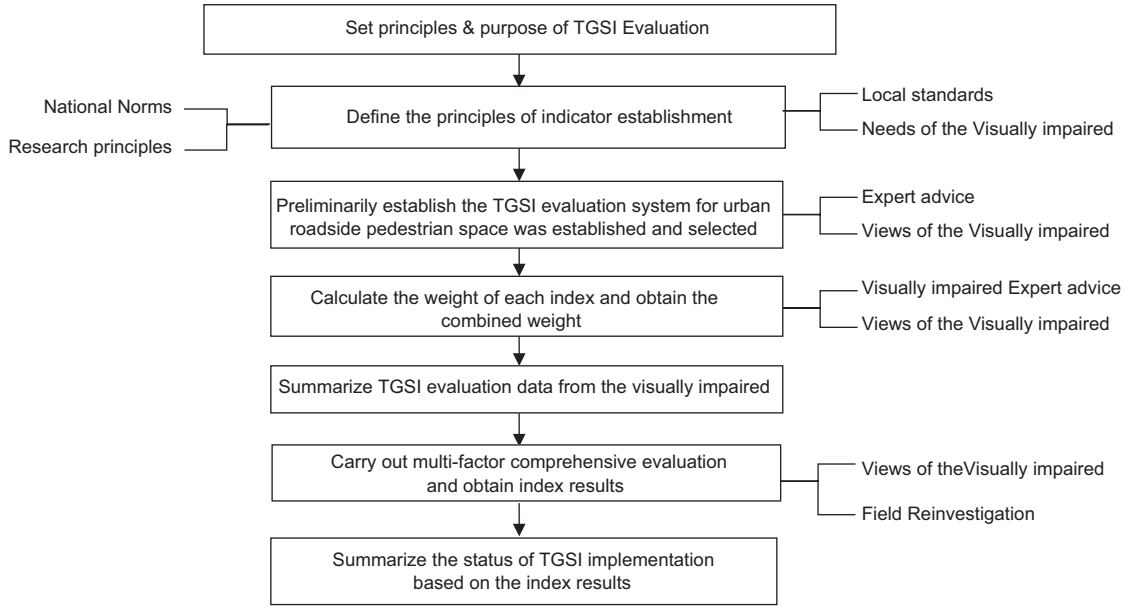


Fig. 3. Evaluation system of TGSIs in urban road pedestrian space

$$E = W \cdot R = (w_1, w_2, \dots, w_k) \cdot \begin{bmatrix} r_{11} & r_{12} & \dots & r_{1n} \\ r_{21} & r_{22} & \dots & r_{2n} \\ \dots & \dots & \dots & \dots \\ r_{k1} & r_{k2} & \dots & r_{kn} \end{bmatrix} \quad (11)$$

E represents the value of the final evaluation results for each criterion layer indicator relative to the overall evaluation.

If $e_k = \max(e_1, e_2, e_k, \dots, e_n)$, where e_k is the k th vector of the vectors, then according to the principle of maximum membership within fuzzy evaluation, the final evaluation result for the evaluation object belongs to the k th level.

Objects of study

The following principles should be observed during the selection of evaluation objects:

1) Principle of representativeness

The selected evaluation objects must be able to represent the status of TGSIs within all road types in Nanjing's Gulou district.

2) Principle of contrast

According to the characteristics of urban functional zoning, the selected evaluation objects should be widely distributed in the central areas, marginal areas, and new areas of Gulou district for the convenience of subsequent comparative analysis.

3) Difference principle

There should be some variation among the selected evaluation objects. Additionally, homogenization of road features in the same region should be avoided as far as possible when randomly selecting the survey objects.

4) Stability principle

The selected evaluation objects should remain unchanged over a certain period.

Sample selection

In this study, a random sampling method was used to select 18 evaluation samples from different ranks of roads in the old and in the new areas. Among them, the evaluation object selection should balance the attributes of each area. Each evaluation object was a TGSi-demarcated pathway extracted randomly from the pedestrian space of each road in Gulou district (**Fig. 4**). The ethics committee of China university of mining and technology in Xuzhou approved the study, and informed consent was obtained from the participants.

RESULTS AND DISCUSSION

Statistical analysis of the evaluation results

Final analytical result

The final quality index result indicates (**Table III**) that TGSIs in 50 % of the evaluation objects have

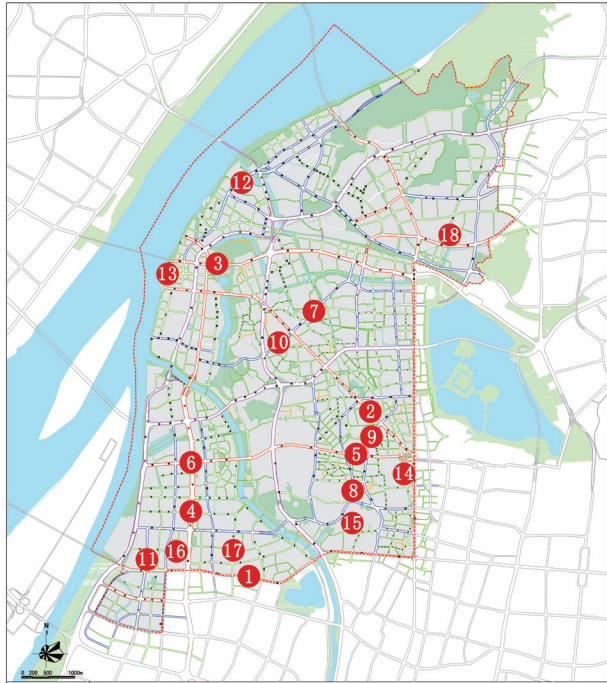


Fig. 4. Evaluation system of TGSIs in urban road pedestrian space

an overall rating of “fine” or better. It can be seen from the scatter distribution that the overall TGSi quality index of the evaluation objects is polarized. The semantic scale value of “bad” appears in the security evaluation of TGSIs in the Beijing West Road pedestrian space (Fig. 5).

The evaluation objects marked as “fine” or better accounted for 50 % of the total. Half of the standardization indexes are above and below normal, indicating that the standardization of TGSIs needs to be further improved. TGSi evaluation objects with a security index of “fine” or better accounted for 50 % of the total evaluation objects. It can be seen from the scatter distribution that the security indexes of the evaluation objects are contrasting. The security evaluation of pedestrian space TGSIs on Beijing West Road showed the result “bad”. Only seven of the TGSi evaluation objects, numbered 9, 10, 11, 12, 15, 16, and 17, had an accessibility index of “fine” or better, and made up 38.8 % of the total. Most TGSIs had insufficient accessibility, and TGSIs in the pedestrian space of Beijing West Road and Ninghai Road were rated as “poor” on the semantic scale. Seven evaluation objects had a TGSi continuity index of “fine” or better, accounting for 38.8 % of the total.

The continuity of TGSIs was at or below “average” for most of the evaluation objects, and a semantic

scale value of “poor” was arrived at in the TGSi continuity evaluation of the West Beijing Road and Ninghai Road. The results for the continuity index of the evaluation objects are polarizing. Of the total evaluation objects 44.4 % had a TGSi comfort index value of “fine” or better. The comfort indexes of Beijing Road, Fujian Road, Ninghai Road, and Anhuan Road were all “poor”, but none of the evaluation objects had the semantic scale value “bad”. An aesthetic index rating of “fine” or better was arrived at for the TGSIs in Jianning Road, Lhasa Road, and Caochangmen Road. As previously mentioned, “aesthetic” was used to evaluate the quality of TGSIs from the perspective of urban roadside pedestrian space environment design, and most of the evaluation objects were rated aesthetically poor (Fig. 5).

The key significant variables of TGSi quality

1) Status of TGSi space in different urban areas

The results of the analysis of the comprehensive TGSi quality evaluation are helpful for assessing the development conditions in different urban districts. We can see from **table IV** that the comprehensive scoring and evaluation results for TGSi quality in the new town area are better than those in the old town area.

2) Status of TGSIs along roads at different levels in the road hierarchy

The analysis results are also helpful for discussing the influence of the position of a road within the road hierarchy on the quality of TGSi-demarcated pathways. **Table IV** shows that the comprehensive scoring and evaluation results of TGSi quality on main roads is better than for secondary main roads, and the comprehensive score and evaluation of TGSi quality on secondary main roads is better than that of access roads.

Analysis of current problems

Variation in first-level indicator values with road grade

The evaluation objects in this study are 18 roads with TGSi-demarcated pathways that were randomly selected from those in Gulou’s Binjiang district, Tiebei district, Old town area, and Hexi district, according to the classification criteria of being a main road, secondary main road, or access road.

Overall, the result for TGSi standardization in the evaluation objects is satisfactory. There are slight differences in the evaluation results for TGSIs within different levels of the road hierarchy. TGSIs on main roads have better security evaluations than hierarchically lower roads, and the security of secondary main

TABLE III. DATA SUMMARY OF QUANTITATIVE SCORING OF PRIMARY INDEX

Road type	Road names	Number	Sort order	F_1	F_2	F_3	F_4	F_5	F_6	F
Main roads	Hanzhongmen Street	1	10	2.5804 ordinary	3.2488 ordinary	3.2427 ordinary	2.4805 poor	3.3133 ordinary	3.3296 ordinary	3.0266 ordinary
	Zhongshan North road	2	11	2.4776 poor	3.0868 ordinary	3.1240 ordinary	3.6635 fine	3.1135 ordinary	3.3443 ordinary	2.4856 ordinary
	Jianning Road	3	9	3.5202 fine	3.5247 fine	3.4481 ordinary	4.2563 fine	4.0607 fine	3.8493 fine	3.6043 fine
	Jiangdong North Road	4	3	4.3471 fine	4.2972 fine	3.2780 ordinary	3.6800 fine	4.0841 fine	3.4907 ordinary	4.1208 fine
	Beijing West Road	5	18	1.8361 poor	1.3927 bad	1.2334 bad	1.2173 bad	1.6325 poor	1.7593 poor	1.5238 poor
	Caochangmen Road	6	2	4.1307 fine	4.4807 fine	3.4348 ordinary	3.7809 fine	4.2206 fine	3.5742 ordinary	4.1754 fine
Secondary main roads	Fujian Road	7	15	2.2049 poor	1.9189 poor	2.1082 poor	1.9275 poor	2.3558 poor	2.4754 poor	2.0758 poor
	Ninghai Road	8	17	1.9985 poor	1.5861 poor	1.3438 bad	1.3438 bad	1.9127 poor	1.4010 bad	1.7074 poor
	Yunnan Road	9	12	2.6082 ordinary	1.5983 poor	4.2939 fine	2.3490 poor	3.1108 ordinary	2.3990 poor	2.3792 poor
	Chahaer Road	10	4	4.0615 fine	4.3243 fine	3.5060 ordinary	4.2166 fine	3.9543 fine	3.3301 ordinary	4.0886 fine
	Qingjiang Road	11	7	3.8856 fine	4.1938 fine	3.5187 ordinary	3.3574 ordinary	3.2699 ordinary	3.1984 ordinary	3.8819 fine
	Pagoda Bridge West Street	12	5	4.0304 fine	4.3025 fine	3.5449 fine	2.9321 ordinary	3.8786 fine	3.2837 ordinary	4.0027 fine
Access roads	Riverside Road	13	8	3.5227 fine	3.9201 fine	3.0807 ordinary	2.8363 ordinary	4.1018 fine	3.4124 ordinary	3.6532 fine
	Tientsin Road	14	14	2.1151 poor	2.0768 poor	1.8111 poor	2.2000 poor	2.3397 poor	2.0471 poor	2.0832 poor
	Lhasa Road	15	6	3.6868 fine	4.1412 fine	4.1011 fine	4.1374 fine	3.8312 fine	4.3009 fine	3.9883 fine
	Dongbao Road	16	13	2.8969 ordinary	1.3748 poor	3.7523 fine	2.3456 poor	2.6614 ordinary	2.0360 poor	2.2550 poor
	Nenjiang Road	17	1	4.3777 fine	4.4601 fine	4.0510 fine	4.3220 fine	3.9719 fine	3.2564 ordinary	4.3056 fine
	Anhuai Road	18	16	2.9649 ordinary	1.5737 poor	1.5068 poor	1.6272 poor	1.8550 poor	1.3873 bad	1.9833 poor

road and access roads achieved contrasting results, with equal numbers of “fine” and “poor” evaluations.

None of the first level indicators received an evaluation of “good” in the semantic scale, which indicates that there are problems to some degree with

the quality of TGSIs on all types of roads in Gulou District. The evaluation results for the new city area are generally better than those for the Laocheng area, and only the aesthetic evaluation provided a fairly consistent result.

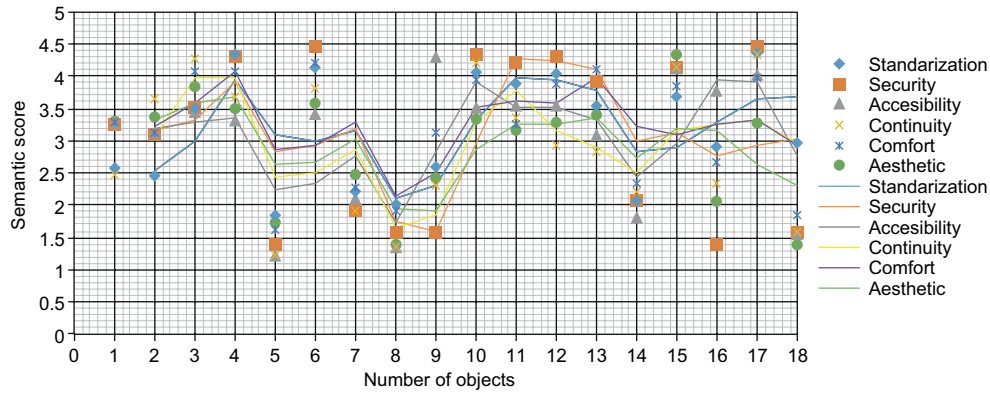


Fig. 5 Distribution of indicator results

TABLE IV. QUALITY SCORES FOR TGSI SPACE IN DIFFERENT DISTRICTS.

Urban areas	Road names	Road hierarchy	number	F	TGSI quality
Old town area	Hanzhongmen Street	Main road	1	3.0263	ordinary
	Zhongshan North road		2	2.4856	poor
	West Beijing Road		5	1.5238	poor
	Fujian Road	Secondary main road	7	2.0757	poor
	Ning Hai Road		8	1.7074	bad
	Yunnan road		9	2.3792	poor
	Tientsin Road	Access road	14	2.0832	poor
	Lhasa Road		15	3.9883	fine
	An Huai Road		18	1.9833	poor
New town area	Jianning Road	Main road	3	3.6043	fine
	Jiangdong North Road		4	4.1208	fine
	Caochangmen Street		6	4.1754	fine
	Chahaer Road	Secondary main road	10	4.0886	fine
	Qingjiang Road		11	3.8819	fine
	Pagoda Bridge West Street		12	4.0027	fine
	Riverside Road	Access road	13	3.6532	fine
	Dongbao Road		16	2.2550	poor
	Nenjiang Road		17	4.3056	fine

Spatial variations in TGSI quality

1) Evaluation and comparison of the present state of TGSIs on different road types.

In general, the results of TGSI quality evaluation for main roads are slightly better than those for secondary main roads and access roads, and a semantic scale rating of “bad” appears for one secondary main road.

2) Evaluation and comparison of the present state of TGSIs in different urban areas.

The evaluation results for the quality of TGSIs are different for different urban areas. TGSI-demarcated

pathways in the new urban area have a slightly better-quality evaluation than those in the old urban area. For example, the proportion of roads evaluated as “fine” in this regard in the new urban area is 88.89 %, while the proportion rated “fine” in the old area is only 11.11 %. Furthermore, the semantic scale value of “bad” appears once in the evaluation of TGSIs in the old urban area.

However, a rating of “good” did not appear for any of the roads evaluated, indicating that although the evaluation results for TGSIs in Nanjing’s Gulou District are different at different levels in the road

hierarchy and in different urban areas, the results are not ideal. Through the targeted analysis of the evaluation data, we can summarize the current state of TGSIs so as to improve their spatial quality (**Fig. 6**).

Analysis of common problems with TGSIs

Combining the results of evaluation and analysis and the current state of TGSIs in Gulou District, Nanjing, allows the most common problems with pathways for the visually impaired to be identified, as follows.

- 1) The higher the road is within the road hierarchy, the better the quality of TGSIs. Whether in the old city area or the new city area, the comprehensive score for the quality of TGSIs is better for main trunk roads than for sub-trunk roads and spur tracks. The most likely reason for this is that both sides of main trunk roads are more spacious, making the walking experience better than on other grades of roads because the probability of encountering obstacles within TGSIs space is lower than along other roads.
- 2) TGSIs accessibility and aesthetics both received poor evaluations. Pathways for the visually impaired do not have a pleasing visual effect in the urban environment, and the current TGSIs implementation generally lacks reasonable route design.

The characteristics of pathways for the blind have arisen from the historical background of different urban zones, and the influence of the complex urban road environment on the present implementation of TGSIs. The details are as follows:

- 1) The influence of different urban areas' historical backgrounds on the present implementation of TGSIs

Old urban areas generally formed spontaneously and slowly over a long period of time, while new city areas have been newly developed as part of the rapid urbanization process in recent decades.

Owing to the rapid development of urban motorized traffic and the difficulty of urban renewal, it is challenging to maintain the urban road space in the old city area, in order to keep up with the pace of modern urban development. This difficulty leads to congestion in roadside pedestrian spaces in the old city area. While the planning and design of the new city area have always taken motor traffic into account, this is also the main reason for another problematic characteristic of the TGSIs.

- 2) The influence of the complex urban road environment on the present implementation of TGSIs

The complex road environment includes features such as urban rail transit nodes (such as on Pagoda Bridge West Street) and urban road walking space renewal projects (such as on Tiger Road), and urban road pedestrian space is seriously obstructed by natural objects (such as on Ninghai Road) and human beings (such as on Fujian Road). The investigation shows that due to a lack of necessary warnings and guidelines, it is almost inevitable that the visually impaired will walk into a complex, unfamiliar urban road environment from a familiar one.

- 3) Quality of TGSIs on different road types

The evaluation results indicate that the standardization, security, continuity, comfort, and other aspects of TGSIs on main roads are relatively satisfactory, and secondary main road TGSIs are sufficient in terms of standardization and security.

However, access roads only received one satisfactory evaluation, for standardization, and their quality is lower than that of roads further up in the hierarchy.

- 4) Quality of TGSIs in different areas of the city

Factors influencing TGSIs quality in the old city area: Since the reform and opening up began in China, the country has seen major progress in its urbanization. However, many problems have arisen. There has been a lack of thorough design and long-term planning for old city areas within the rapid urbanization process, resulting in problems in the

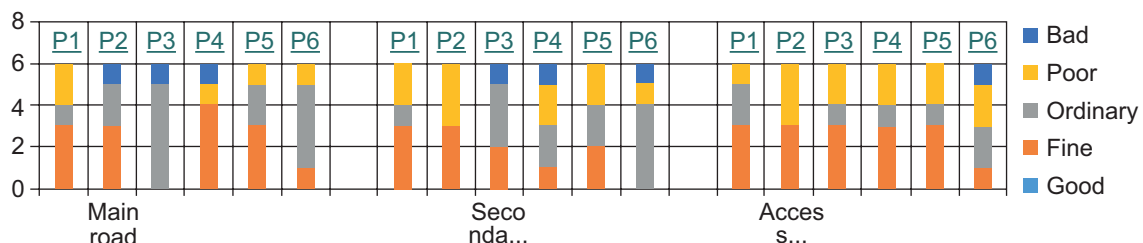


Fig. 6. Distribution of evaluation results for pedestrian spaces on roads of different grades

old city like outdated infrastructure, poor building quality, a chaotic and congested urban traffic network, and a lack of public activity areas and greening in the residential environment. The disadvantages of the old city area are also related to the area being designed around a single center. Many social resources are allocated towards the construction of new areas, resulting in less investment in construction in the old city area. The characteristics of the TGSIs in the old city area are mainly reflected in the following two aspects.

The expansion of urban roads encroaches on pedestrian space, resulting in narrow pedestrian spaces and the encroachment of TGSIs-demarcated pathways in old urban areas. At the same time, the pedestrian space along roads competes for space with roadway trees, and the roots of trees warp and damage the road.

The municipal facilities in the old urban areas are underdeveloped, TGSIs renewal is not timely, and the pathways become severely wear and tear.

Factors influencing TGSIs quality in the new city area: Compared with the old city area, the new city area has wider roads and better facilities, but their management is still not sufficient. The old city area is densely populated and has more visually impaired people. Although the TGSIs system is much better in the new city area, it has a lower utilization rate.

Discussion on improvement measures

TGSIs are common guide facilities in many countries. Under normal circumstances, people with visual impairment can use them to live normal lives within society. TGSIs are an effective guidance method, but the evaluation of the current state of TGSIs in Gulou District, Nanjing, has revealed the existence of several problems. These can be summarized as follows: the structure of TGSIs is not standardized, the spatial position of TGSIs in the city is not good, the TGSIs system is imperfect, and the setting of TGSIs is unreasonable.

Improvements to the TGSIs structure

TGSIs material

At present, the provisions regarding TGSIs material in the national code are relatively vague (Kobayashi, Osaka, Hara, and Fujimoto 2008). Because of the different environments in which the materials used are located, their compressive strength, wear resistance, frost resistance, water absorption, anti-corrosion rate and other indexes will differ, so the influence of the local environment on these characteristics of a pathway for people with visual impairment or blindness should be considered when installing TGSIs. In order to standardize the use of

TGSIs materials, standards should be established for the attributes of different TGSIs materials in different environments (Ranavolo et al. 2011).

TGSIs dimensions

From descriptions of TGSIs by scholars, the specification standard for TGSIs is currently also vague. In combination with the provisions of the Code for Barrier-Free Design (GB50763-2012), this study recommends that the size of TGSIs bricks be based on a modulus of 250 mm. The width of TGSIs can be 250 mm on narrow urban sidewalks and 500 mm in wider sidewalk spaces (Thies et al. 2011; Thies, Jones, Kenney, Howard, and Baker 2011). This measure would be convenient for the popularization and unification of pathways for people with visual impairment or blindness.

Optimization of the location of TGSIs

Position of the TGSIs system along urban roads

In the design of improved TGSIs locations along urban road, it is necessary to integrate vehicle lanes and optimize the separation barriers between motor vehicles and non-motor vehicles to prevent motor vehicles and non-motor vehicles from entering the pavement (Crudden, A. C. J. L. 2017), and to consider the rational layout of non-motor parking spaces, roadway trees, municipal facilities, signs, and human flows.

Position of TGSIs in the road walking space

TGSIs are arranged along the partitioning railings of the parking rack. The partitioning railings can also be used as handrails for the visually impaired. Braille information can be integrated into the partitioning railings to provide additional information for the visually impaired. The inner side of the pavement is a pedestrian-only sidewalk. Vehicles cannot enter, so the interference of vehicles with pedestrians can be avoided.

Improving the TGSIs system

Building a complete TGSIs system

A complete TGSIs system should include TGSIs with supporting Braille maps, Braille station signs, Braille road signs, barrier-free identification signs, audio signal devices at intersection crossings, etc. Furthermore, it should cover all the places and corresponding supporting facilities that visually impaired people use. The system can be divided into that on urban roads, at bus stations, at rail transit stations, in transportation hub buildings, in key urban activity areas, etc. (Table V).

TABLE V. TGSi TRANSPORTATION SYSTEM.

Main types	Concrete content	Key points for setting
Urban road	Urban roads, urban squares, urban green space, parkland scenic spots, commercial blocks (pedestrian streets) at all levels; specifically related to sidewalks for the blind, crossing facilities (pedestrian overpasses, tunnels, crosswalks)	
Bus stations	Blind-guidance paths, braille bus information board, and audio bus information at pedestrian entry points to the bus station	
Rail transit station	TGSIs and traffic barrier-free guiding devices at entrances and exits of stations, ticket gates, ticket offices, platforms, barrier-free vertical elevators, etc.	1. Refer to the national norms and regulations. Discuss the rationality of the requirements of various TGSi facilities in the norms. 2. Conduct a concrete analysis of the TGSi problems based on their current implementation and the needs of the visually impaired and carry out humanized design and improvement of TGSIs.
Transportation hub building	TGSIs and bus barrier-free guidance system in railway stations, inter-city bus stations, passenger ports, civil airport terminal buildings, entrances and exits from the passenger station's front square, ticket office, platform, etc.	
Key urban activity areas	TGSi system around key activity areas of the blind such as massage centers for visually impaired persons, community hospitals, residential areas and schools for visually impaired people	
Traffic auxiliary management facilities	Braille maps, Braille station signs, Braille road signs, information signs, audio signal devices at street at intersection crossings, etc.	

Improving TGSi accessibility

The improvement of TGSi accessibility should be considered from the aspects of the degree of recognition, the reasonableness of its functionality, the degree of TGSi detouring, and the convenience of using TGSIs to reach a destination.

1) Improving TGSi recognition

Improving the effectiveness of TGSi information transmission and replacing worn TGSIs in a timely manner can improve its identifiability (**Fig. 7 a-c**).

2) Reducing the degree of TGSi detouring

According to the survey, the inadequate accessibility of pathways for people with visual impairment or blindness is related to the degree of sinuosity in the pathway. Due to a lack of systematic design of the locations of municipal overhaul wells, TGSi-demarcated routes have been made tortuous to different degrees in order to bypass these wells. Some entrance steps belonging to buildings along the street extend to the middle of the pavement to block TGSi pathways directly. Other obstacles in the pedestrian space along roads are also important contributors to TGSi-pathway sinuosity. Therefore, the degree of TGSi-pathway sinuosity should be taken as a major consideration in overall municipal and TGSi planning, changes in the forms of building entrances

along streets, timely clearing of obstacles in the pedestrian space along urban roads, and so on. The original intention of TGSi setting is to help visually impaired people participate in social activities safely and effectively (Zhai, Huang, Sze, Song, and Hon 2019). Helping these people to avoid obstacles is one of the main tasks of TGSIs. Some obstacles existed long before the TGSi pathway was laid. In this situation, it should be considered appropriate that concessions for TGSIs avoid to be detrimental of the original function (Kang 2019). Some obstacles, such as sharing bicycles and peddlers, should be avoided at the urging of relevant departments. Conversely, some obstacles are caused by poor coordination of urban construction departments or a lack of careful consideration of urban renewal. Municipal facilities such as fire hydrants and isolation belts are in pedestrian space (O Hern and Oxley 2019). Therefore, coordination and cooperation between urban construction departments should be strengthened to avoid such situations.

3) Improving auxiliary facilities to TGSIs

It is difficult to meet the travel needs of visually impaired people so that they can participate in social activities only through TGSIs (Nguyen, Ferro, and Pawluk 2018). Besides TGSIs, visually impaired people also need the assistance of Braille maps,

Braille station signs, TGSi signs, caring signs and audio signal devices at crossings to navigate the walking space of urban roads (**Fig. 7-c**).

Improving the continuity of TGSIs

According to the survey, TGSi continuity is poor in the Gulou District of Nanjing, mainly due to the absence of a TGSi section from the entrance from residential areas to the road, serious encroachment over TGSIs, the absence of pedestrian crosswalk TGSIs, and imperfections in the TGSi system (lack of audio, Braille and other auxiliary hints at necessary locations). These problems can mainly be attributed to TGSIs belonging to the category of municipal and social welfare and only being installed on urban sidewalks, inadequate management of TGSi obstacle removal, and serious damage and wear to TGSIs. As mentioned above, damage and wear to TGSi need to be rectified by relevant departments in a timely manner.

Almost all the respondents had experienced accidents because of their eyesight. It should be noted that in most cities in China, non-motorized vehicles (electric vehicles and bicycles) and pedestrians are mixed, and most of the accidents suffered by the visually impaired people were with non-motorized vehicles on the sidewalk. Other causes include falling downstairs, falling into holes or pits, colliding with objects on the sidewalk, stepping into gaps between buses and platforms, hitting building scaffolding and glass doors, and tripping over obstacles in the road. The illegal parking of cars on the sidewalk is a phenomenon that exists in every city in China. The existence of various obstacles is the external factor that affects the continuity of TGSIs.

Setting TGSIs to suit local conditions

At present, TGSi-laying lacks pertinence. Uniform and extensive laying of TGSIs is wasteful. When laying TGSIs, we should respect the existing road conditions, consider the density of TGSIs from the perspective of the density of the visually impaired, and coordinate the setting of TGSIs with the type of urban road.

Take full account of existing road conditions

Gulou District is the main urban area of Nanjing City. The high-intensity development of the city has caused a large amount of traffic pressure. As a result, the pedestrian space along roads has been compressed repeatedly: the expansion of motor lanes has led to the retreat of sidewalks. Along some roads (such as Ninghai Road) walking space is mixed with urban street tree space. Ninghai Road is crowded, with huge, dense trees, shared bicycles, trash cans, streetlights, and other facilities scattered along a pavement that is about 2 m wide. There are obstacles to TGSi-guided routes at almost every meter along the pavement (**Fig. 7-d**). Added together with the need of other pedestrians to pass along the pavement, these issues have a huge impact on travel by the visually impaired and the setting of TGSIs.

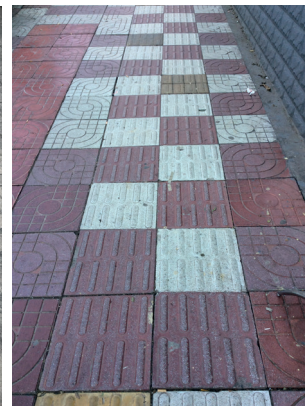
Therefore, observing the existing spatial constraints of roads requires that the municipal authorities investigate the mixing of pedestrian space and urban roadside tree space and put forward reasonable measures to ensure the integrity of roadside pedestrian space. However, reasonable TGSi-setting methods should be put forward after careful and rigorous discussion in places where limited space is available



7-a The new TGSi is easily recognizable



7-b The old TGSi was hard to read



7-c The TGSi are arranged like a checkerboard



7-d Cramped conditions along Ninghai road

Fig. 7. Status of TGSIs

such as old urban areas, like has been done recently in Gulou District. For example, a recent practice in Gulou District has been to set up prompts indicating the pathway for the visually impaired in key areas, and to remove or smooth the original pathways for the visually impaired in other parts of the road to ensure the normal function of the road pedestrian space.

The important parts of the road were set up to indicate the TGSi route, and the other parts were efficiently cleaned up to ensure the normal functioning of the roadside pedestrian space.

Considering the density of the visually impaired

The reasonable setting of TGSIs should be based on the density of visually impaired people. According to the survey, problems such as an imperfect TGSi system, serious wear and tear on TGSIs, and serious encroachment on TGSi-demarcated routes are common in the old city area, whereas the new city area commonly has a new, complete TGSi system, but the utilization rate is lower. The reason is people with visual impairment generally think that medical services are better and that the distance to employment locations is shorter and travel to them is more convenient in the old city area, so they prefer to work there. While the new urban area is in the stage of attracting urban people, the medical system is not yet as good, and employment opportunities are few. Although the pedestrian environment along its urban roads is good, it is currently relatively empty and is being wasted. Therefore, full consideration of the characteristics of the old and new cities indicates that TGSIs with complete functionality and developed associated systems must be set up in places in which visually impaired people are densely concentrated. In the next few years, there will be little activity by the visually impaired in the new urban areas, so the allocation of TGSIs in such locations can be reduced. Reasonable planning of TGSi types and setting methods based on the spatially varying density of the visually impaired is conducive to the improvement of the urban environment for the blindness.

CONCLUSIONS

1. Based on analysis of evaluation of the present state of TGSi implementation in Gulou District, Nanjing, we find that the present quality of roadside TGSIs in the old city area of the district is worse than in the new city area, that it is worse along roads lower in the road-grade hierarchy than along higher-grade roads.
2. Specific problems have arisen in the old city area such as narrowing of the pedestrian space due to road expansion, conflict between pedestrian space and tree space, encroachment onto TGSi-demarcated routes, a large amount of wear and tear, and a lack of regular renewal. The new town area has wide roads and better TGSi quality but a lower utilization rate. The problems with the current implementation of TGSIs have some common causes, such as inconsistent planning, non-standard construction, inadequate management, and unreasonable design.
3. The existing TGSi implementation should be improved from four aspects: improving the structure of TGSIs, optimizing the location of TGSIs, perfecting the TGSi system, and adjusting TGSi-setting according to local conditions. These measures would significantly improve the quality of TGSi-demarcated walking space in Gulou District.
4. The historical background of different urban areas and the complex urban road environment are the main factors influencing the characteristics of the TGSi environment. Owing to the rapid development of urban motor traffic and the difficulty of urban renewal, the urban road space in the old city area cannot maintain the same rate of progress as rapid modern urban development, which leads to further challenges.

This study enriches academic theory in the field of barrier-free design and TGSi status evaluation and offers guidance for the practice of TGSi setting in urban roadside pedestrian space.

It is pertinent to explain that different from traditional traffic safety surveys and evaluations, due to the uniqueness of the visually impaired population, they are challenging to relocate, and mostly live and work in schools or massage parlors for the blind. Interviews with the visually impaired in the indicator construction stage, the process of on-site experience in the evaluation stage and the conclusion of the evaluation through dialogue require time and considerable financial resources, so the sample size of this study is small. In the follow-up research, if technical conditions and equipment permit, the research team will use AI technology to record the surrounding environment of the evaluated road. Additionally, the team will use voice input to synchronize the road condition information instantaneously, so that the visually impaired group can make authentic evaluations when they are not actually experiencing the on-site environment. Reducing the difficulty of

the evaluation process will also help increase the sample size. In future research, the research team will incorporate ideas such as the establishment of an AHP-Entropy composite matter-element urban transportation sustainable development evaluation model. Then, the research team will try to establish a combined evaluation model based on the improvement of the AHP method such as the analytic hierarchy process-data envelopment analysis (AHP-DEA) model, and the AHP-Entropy weight method. A more scientific and reasonable evaluation system (Chiara D'Alpaos et al. 2020) will be incorporated to verify the accuracy of different sources of data, such as subjective evaluation and objective measured data, in the evaluation indicators. The evaluation index system of this study can provide a reference for TGSI evaluation in other cities in China, and the evaluation results can also directly provide a scientific basis for TGSI quality improvement in Gulou District, Nanjing.

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REFERENCES

- Aghaabbasi M., Moeinaddini M., Zaly Shah M., Asadi-Shekari Z. and Arjomand Kermani M. (2018). Evaluating the capability of walkability audit tools for assessing sidewalks. *Sustainable Cities and Society* 37, 475-484. <https://doi.org/10.1016/j.scs.2017.12.001>
- Akkaya G., Turanoğlu B. and Öztaş S. (2015). An integrated fuzzy AHP and fuzzy MOORA approach to the problem of industrial engineering sector choosing. *Expert Systems with Applications* 42(24), 9565-9573. <https://doi.org/10.1016/j.eswa.2015.07.061>
- Chiara D'Alpaos F.A. (2020). Urban quality in the city of the future: A bibliometric multicriteria assessment model. *Ecological Indicators* 117, 1-12. <https://doi.org/10.1016/j.ecolind.2020.106575>.
- Courtney A. and Chow H. M. (2000a). A study of tile design for tactile guide pathways. *International Journal of Industrial Ergonomics* 25(6), 693-698. [https://doi.org/10.1016/S0169-8141\(99\)00051-7](https://doi.org/10.1016/S0169-8141(99)00051-7)
- Courtney A. and Chow H. M. (2000b). A study of tile design for tactile guide pathways. *International Journal of Industrial Ergonomics* 25(6), 693-698. [https://doi.org/10.1016/S0169-8141\(99\)00051-7](https://doi.org/10.1016/S0169-8141(99)00051-7)
- Crudden A.C.J.L. (2017). Stress associated with transportation: a survey of persons with visual impairments. *Journal of Visual Impairment and Blindness* 3(111), 219-230. <https://doi.org/10.1177/0145482X1711100303>
- Da Silva F. M., Gachet Barbosa L. A., Lintz R.C.C. and Jacintho A. E. P. G. 2015. Investigation on the properties of concrete tactile paving blocks made with recycled tire rubber. *Construction and Building Materials* 91, 71-79. <https://doi.org/10.1016/j.conbuildmat.2015.05.027>
- Dursin A.G. 2012. Information design and education for visually impaired and blind people. *Procedia Social and Behavioral Sciences* 46, 5568-5572. <https://doi.org/10.1016/j.sbspro.2012.06.477>
- Fan G., Zhong D., Yan F. and Yue P. (2016). A hybrid fuzzy evaluation method for curtain grouting efficiency assessment based on an AHP method extended by D numbers. *Expert Systems with Applications* 44, 289-303. <https://doi.org/10.1016/j.eswa.2015.09.006>
- Gitelman V., Levi S., Carmel R., Korchatov A. and Hakert S. (2019). Exploring patterns of child pedestrian behaviors at urban intersections. *Accident Analysis and Prevention* 122, 36-47. <https://doi.org/10.1016/j.aap.2018.09.031>
- Hopkins K., Kass S. J., Blalock L. D. and Brill J. C. (2017). Effectiveness of auditory and tactile crossmodal cues in a dual-task visual and auditory scenario. *Ergonomics* (5), 692-700
- Kang B. 2019. Identifying street design elements associated with vehicle-to-pedestrian collision reduction at intersections in New York City. *Accident Analysis and Prevention* 122, 308-317. <https://doi.org/10.1016/j.aap.2018.10.019>
- K. Hiroto and H. Katsumi. 2019 A wearable walking support system to provide safe direction for the blind. 34th International Technical Conference on Circuits/Systems, Computers and Communications (ITC-CSCC), JeJu, Korea (South). 1-4, <https://doi.org/10.1109/ITC-CSCC.2019.8793305>.
- Kobayashi Y., Osaka R., Hara T. and Fujimoto H. (2008). How accurately people can discriminate the differences of floor materials with various elasticities. *IEEE Transactions on Neural Systems and Rehabilitation*

- Engineering 16(1), 99-105. <https://doi.org/10.1109/TNSRE.2007.910283>
- Kobayashi Y., Takashima T., Hayashi M. and Fujimoto H. (2005). Gait analysis of people walking on tactile ground surface indicators. *IEEE Transactions on Neural Systems and Rehabilitation Engineering* 13(1), 53-59. <https://doi.org/10.1109/TNSRE.2004.841880>
- Li W., Liang W., Zhang L. and Tang Q. (2015). Performance assessment system of health, safety and environment based on experts' weights and fuzzy comprehensive evaluation. *Journal of Loss Prevention in the Process Industries* 2015, 35, 95-103. <https://doi.org/10.1016/j.jlp.2015.04.007>
- Won M., Shrestha A., Park K. and Eun Y. (2020). Safer-Cross. Enhancing pedestrian safety using embedded sensors of smartphone. *IEEE Access* (8), 49657-49670. <https://doi.org/10.1109/ACCESS.2020.2980085>.
- Mizuno T., Nishidate A., Tokuda K., and Arai K. (2008). Installation errors and corrections in tactile ground surface indicators in Europe, America, Oceania and Asia. *IATSS Research* 32(2), 68-80. [https://doi.org/10.1016/S0386-1112\(14\)60210-7](https://doi.org/10.1016/S0386-1112(14)60210-7)
- Nguyen A. M., Ferro T. J. and Pawluk D. T. V. (2018). Effectiveness of using local cues to indicate perspective in tactile diagrams for people with visual impairments. *Journal of Visual Impairment and Blindness* (6), 731-744. <https://doi.org/10.1177/0145482X1811200608>
- O'Hern S. and Oxley J. (2019). Pedestrian injuries due to collisions with cyclists Melbourne, Australia. *Accident Analysis and Prevention* 8(122), 295-300. <https://doi.org/10.1016/j.aap.2018.10.018>
- Øvstedal L. R., Lid, I. M. and Lindland T. (2005). How to evaluate the effectiveness of a tactile surface indicator system? *International Congress Series* 2005, 1282, 1051-1055. <https://doi.org/10.1016/j.ics.2005.04.005>
- Padzi F. A., Ibrahim F. and Karim N. A. (2013). Incongruent installation of tactile ground surface indicator toward visual impaired people's need: Masjid Jamek Station. *Procedia - Social and Behavioral Sciences* 101, 130-139. <https://doi.org/10.1016/j.sbspro.2013.07.186>
- Pluijter N., de Wit L. P. W., Bruijn S. M. and Plaisier M. A. (2015). Tactile pavement for guiding walking direction: An assessment of heading direction and gait stability. *Gait and Posture* 42(4), 534-538. <https://doi.org/10.1016/j.gaitpost.2015.08.009>
- Ranavolo A., Conte C., Iavicoli S., Serrao M., Silvetti A., Sandrini G.,... Draicchio F. (2011). Walking strategies of visually impaired people on trapezoidal- and sinusoidal-section tactile ground surface indicators. *Ergonomics* 54(3), 246-256. <https://doi.org/10.1080/00140139.2010.548533>
- Thies S. B., Jones R. K., Kenney L. P., Howard D. and Baker R. (2011). Effects of ramp negotiation, paving type and shoe sole geometry on toe clearance in young adults. *Journal of Biomechanics* 44(15), 2679-2684. <https://doi.org/10.1016/j.jbiomech.2011.07.027>
- Thies S. B., Kenney L. P. J., Howard D., Nester C., Ormerod M., Newton R.,... MacLennan H. (2011). Biomechanics for inclusive urban design: Effects of tactile paving on older adults' gait when crossing the street. *Journal of Biomechanics* 44(8), 1599-1604. <https://doi.org/10.1016/j.jbiomech.2010.12.016>
- Total D., Menon M., Jones-Hershinow C., Barton K. and Gates D. H. (2019). The impact of ankle-foot orthosis stiffness on gait: A systematic literature review. *Gait and Posture* 69, 101-111. <https://doi.org/10.1016/j.gaitpost.2019.01.020>
- Tyagi S., Agrawal S., Yang K. and Ying H. (2017). An extended fuzzy-AHP approach to rank the influences of socialization-externalization-combination-internalization modes on the development phase. *Applied Soft Computing* 16(10), 505-518. <https://doi.org/10.1016/j.asoc.2016.10.017>
- Almeida X. M.M.F., Martins L. B. and Lima F. J. (2015). Analysis of wayfinding strategies of blind people using tactile maps. *Procedia Manufacturing* 3, 6020-6027. <https://doi.org/10.1016/j.promfg.2015.07.716>
- Yi K., Kiyotaka F. and Yoichi K. (2018). Evaluation of the influence of roadside non-walking spaces on the pedestrian environment of a Japanese urban street. *Sustainable Cities and Society* 43, 21-31. <https://doi.org/10.1016/j.scs.2018.07.009>
- Zhai X., Huang H., Sze N. N., Song Z. and Hon K. K. (2019). Diagnostic analysis of the effects of weather condition on pedestrian crash severity. *Accident Analysis and Prevention* 122(10), 318-324. <https://doi.org/10.1016/j.aap.2018.10.017>
- Zhang W., Zhou C., Huang W., Tao H., Wang K., Feng Z. and Hu Z. (2019). Investigating factors affecting riders' behaviors of occupying motorized vehicle lanes on urban streets. *Accident Analysis and Prevention* 122(9), 127-133. <https://doi.org/10.1016/j.aap.2018.09.025>