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Investigation of the Needs and Design Innovation for Visually Impaired-Friendly Bus Stop Based on the Kano Model

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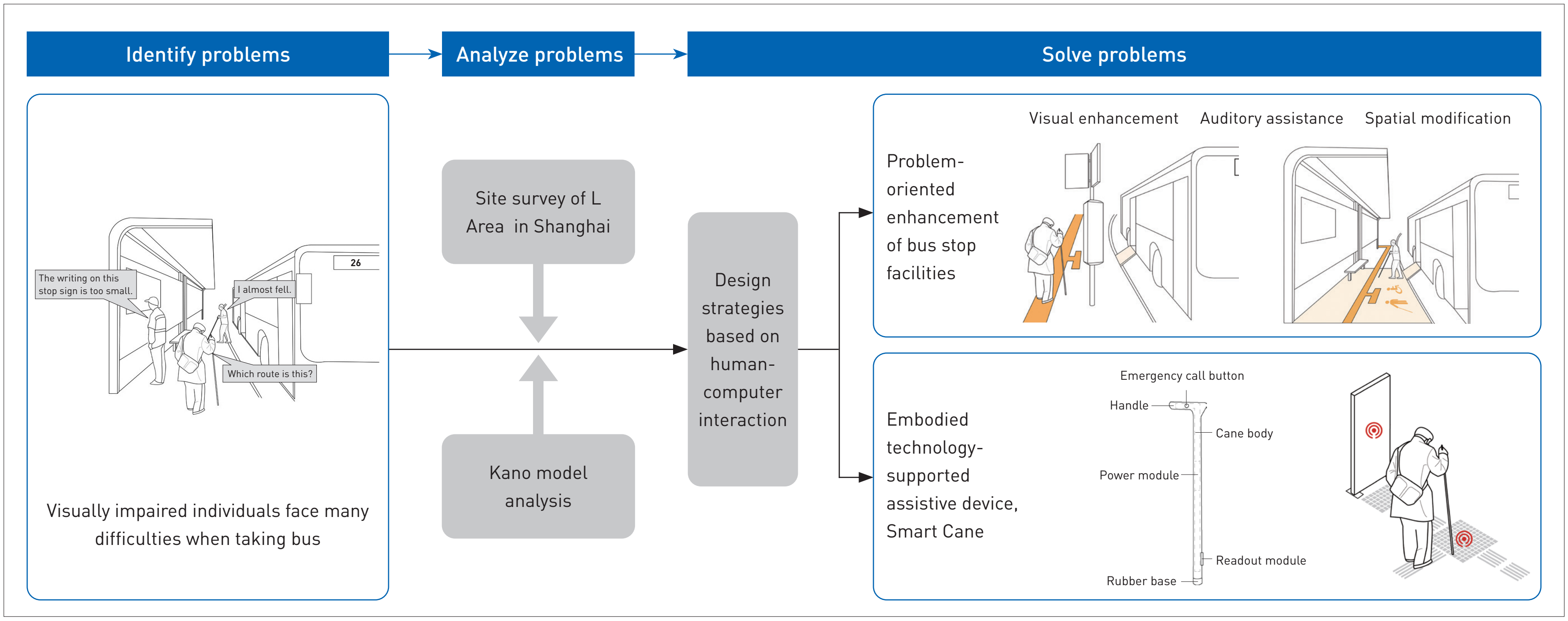
GRAPHICAL ABSTRACT



ABSTRACT

Bus stops are a critical component of urban infrastructure in modern cities. However, there is a notable research gap regarding the accessibility of bus stop facilities for visually impaired passengers. Using the L Area in Shanghai as a case study, research findings reveal significant deficiencies in both the long-distance recognition and accessible facilities of bus stops within the "15-minute community-life circle." Using the Kano model, this study classifies and prioritizes the needs for visually impaired passengers: large-font bus stop sign is a must-be need; audio announcements for bus arrivals are a one-dimensional need; audio announcements for the bus stop location, eliminating the vertical gap between the bus floor and the platform, and establishing an accessible boarding area are attractive needs. The study proposes design strategies for bus stop facilities, including a phased improvement approach for different bus stop types, and the embodied technology-supported assistive device—Smart Canes. This research not only responds to the global academic discourse on inclusive cities, but also contributes to promoting inclusive urban development in practice.

KEYWORDS

Bus Stop Facilities; Visually Impaired-Friendly; Accessible Design; Kano Model; Embodied Technology; Inclusive City

HIGHLIGHTS

- Uses Kano model to analyze visually impaired passengers' needs for accessible bus stops
- Proposes a phased enhancement approach for different bus stops based on problem-oriented analysis
- Develops an embodied technology-based smart assistive device for visually impaired passengers' bus travel

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1 Introduction

In China, the population of visually impaired people is estimated at approximately 17 million[1]. Public transportation infrastructure—including bus stops—plays a critical role in supporting the mobility of such individuals. With the advancement of global urbanization, the creation of inclusive cities has become an globally important concern①[2]. In China, the construction of accessible public transportation facilities began in the 1980s. In recent years, a series of policies have specified requirements for the accessible design and operation of public transportation facilities②, and the construction of accessible public transportation facilities largely involves the modification of buses. However, accessible buses in major cities are still at a pilot stage, remaining a gap before their widespread adoption, and accessible bus stops have received limited attention[3][4]. Therefore, this study investigated the current status of community bus stop facilities, employed the Kano model to analyze the needs of visually impaired passengers, established a systematic approach to improving the accessibility of bus stop facilities, and ultimately proposed optimization strategies of creating accessible bus stops for visually impaired population. This research not only responds to the global academic discourse on inclusive cities, but also contributes to promoting inclusive urban development in practice.

2 Literature Review

2.1 Research on Bus Stop Facilities

Domestic and international existing research on bus stops can be categorized into three themes: urban planning and design, inclusive design and accessible environments, and intelligent technologies and smart cities.

For research on urban planning and design, scholars both domestically and internationally generally focus on the interactions between bus stops and urban spaces. For example, Genrong Cao et al. argued that the construction of inclusive urban street spaces should place significant emphasis on public transportation[5]; Zhong Xing et al. suggested that bus stop density has a significant impact on the vibrancy of urban streets[6]; Nur'Amirah Mhd Noh et al. evaluated acceptable walking distance to bus stops, finding access coverage proportional to catchment radius and walking behavior dependent on pathway availability[7]; John H. E. Taplin et al. proposed that optimizing the location of bus stops and the design of bus routes can enhance the walkability of residential areas[8]; Elisabetta Vitale Brovarone explored the potential role of bus stops in urban environments and proposed design principles[9].

Research on inclusive design and accessible environments often focuses on passengers' experience around bus stops. For example, Xuguang Zheng explored the design principles of bus

① In 2001, the United Nations Human Settlements Programme (UN-Habitat) firstly defined "inclusive cities" in the *Inclusive Cities Initiative—The Way Forward* stating that "it is a place where everyone, regardless of their economic means, gender, race, ethnicity or religion, is enabled and empowered to fully participate in the social, economic and political opportunities that cities have to offer." Since then, its meaning and requirements have been further expanded in multiple editions of the Status of the World's Cities reports (2008–2023) and UN-Habitat annual reports.

② The *Design Specifications for Urban Roads and Buildings for Disabled Accessibility (Trial)*, issued in July 1986, was the first Chinese policy for creating accessible urban environments. Recent policy documents include the *Codes for Accessibility Design* (2012), the *Implementation Opinions on Promoting the "Status Council Guidelines for the Priority Development of Public Transport in Cities"* (2013), the *Regulations on Urban Bus and Trolleybus Passenger Transport Management* (2017), the *Implementation Opinions on Further Strengthening and Improving Travel Services for the Elderly and Disabled* (2018), *and the Outline for the Construction of a Strong Transportation Nation* (2019).

stops from a human-centered perspective[10]; Yiping Hu et al. conducted an analysis of passenger boarding behaviors, offering theoretical support for the design of bus stop facilities[11]; Zhou Yuan et al. identified five types of public service facilities—including bus stops—constituting the essential daily mobility needs of passengers with physical disabilities[12], and analyzed the current status and patterns of accessible environment construction at bus stops[13]; Chuli Qu et al. developed a hierarchical model of passenger needs based on the waiting experience at bus stops[14]; Lidia P. Kostyniuk et al. pointed out that low-floor buses significantly improve accessibility and convenience for elderly passengers and people with disabilities[15]; Manuela Pires Rosa et al. conducted a pilot study proposing the development of bus stops characterized by accessibility, intelligent features, and sustainability[16].

In terms of intelligent technologies and smart cities, the recent development of smart cities has also driven research related to bus stops. For example, Naichuan Deng designed intelligent functions for bus stops based on existing smart bus systems[17]; Thair A. Salih et al. developed a smart system designed to aid users in locating bus routes, estimating arrival times, and accessing other transportation information[18]; Nishant Singh et al. suggested employing artificial intelligence techniques to forecast bus arrival times[19]; Víctor Manuel Padrón Nápoles et al. proposed the development of a prototype for inclusive smart bus stops within the context of smart cities[20].

This study evaluated the current status of bus stops within urban spaces, analyzed the accessibility needs of visually impaired passengers, and addressed the intelligent technologies of bus stop facilities, responding to the three themes above.

2.2 Kano Model

The Kano model is named after Professor Noriaki Kano of Tokyo University of Science[21]. The model is conducted via the Kano questionnaire, which is a specialized Likert scale consisting of pairs of questions for each attribute of a given product/service. Each pair of questions includes one that explores the respondents' feelings when an attribute is fulfilled, known as the "functional question," and the other examines their feelings when the attribute is not fulfilled, referred to as the "dysfunctional question." Respondents are required to choose from five options—like, must-be, neutral, live with, and dislike[22]—when answering these questions. Their answers lead to a total of 25 possible combinations, corresponding to six need categories: must-be (M), one-dimensional (O), attractive (A), indifferent (I), reverse (R), and questionable (Q) (Table 1). The absence of the must-be need significantly diminishes user satisfaction; however, its presence does not markedly increase satisfaction levels. When the one-dimensional need is fulfilled, user satisfaction improves proportionally, while its absence leads to reduced satisfaction. The absence of the attractive need causes no dissatisfaction, yet its presence substantially enhances satisfaction. The indifferent need generates no measurable impact on satisfaction regardless of its implementation. The reverse need negatively affects satisfaction when implemented, and all questionable results should be excluded from analysis[22].

Table 1: 25 possible combinations of Kano model responses

		Dysfunctional question				
		Like	**Must-be**	**Neutral**	**Live with**	**Dislike**
Functional question	Like	Q	A	A	A	O
	Must-be	R	I	I	I	M
	Neutral	R	I	I	I	M
	Live with	R	I	I	I	M
	Dislike	R	R	R	R	R

However, in practical applications, this classification sometimes proves insufficient for in-depth research needs. Therefore, C. Berger et al. proposed the customer satisfaction coefficient[22]. Based on the customer's satisfaction and dissatisfaction, a four-quadrants importance grid can be constructed to further classify needs by measuring the explicit importance and implicit importance of each attribute③.

At present, the analytical application of the Kano model has expanded into a broader range of fields, such as architectural research involving various types of public spaces[23][24], as well as studies on elderly-friendly design[25][26]. Some studies have demonstrated the effectiveness of Kano model for improving the design for visually impaired passengers. For example, Mingze

③ The calculation formula are as follows: explicit importance = (O+M)/(A+O+M+I); implicit importance = (A+O)/(A+O+M+I). In the four-quadrant grid, attributes that fall within the first quadrant are categorized as O; those in the second quadrant are categorized as A; those in the third quadrant are considered I; and those in the fourth quadrant are identified as M. The need hierarchyis: M > O > A > I. Within each category, items are ranked in descending order based on their implicit importance values.

Shi applied the model to offer new perspectives for the design of assistive products for visually impaired individuals[27]; Jinge Xuan et al. conducted classification and prioritization of functional requirements for outdoor assistive devices for visually impaired individuals based on the model[28]. Compared with conventional survey methods, the Kano model witnesses significant advantages in addressing diverse needs and is well-suited for investigating visually impaired-friendly bus stop facilities.

3 Case Study: The Survey of Bus Stop Facilities in the L Area

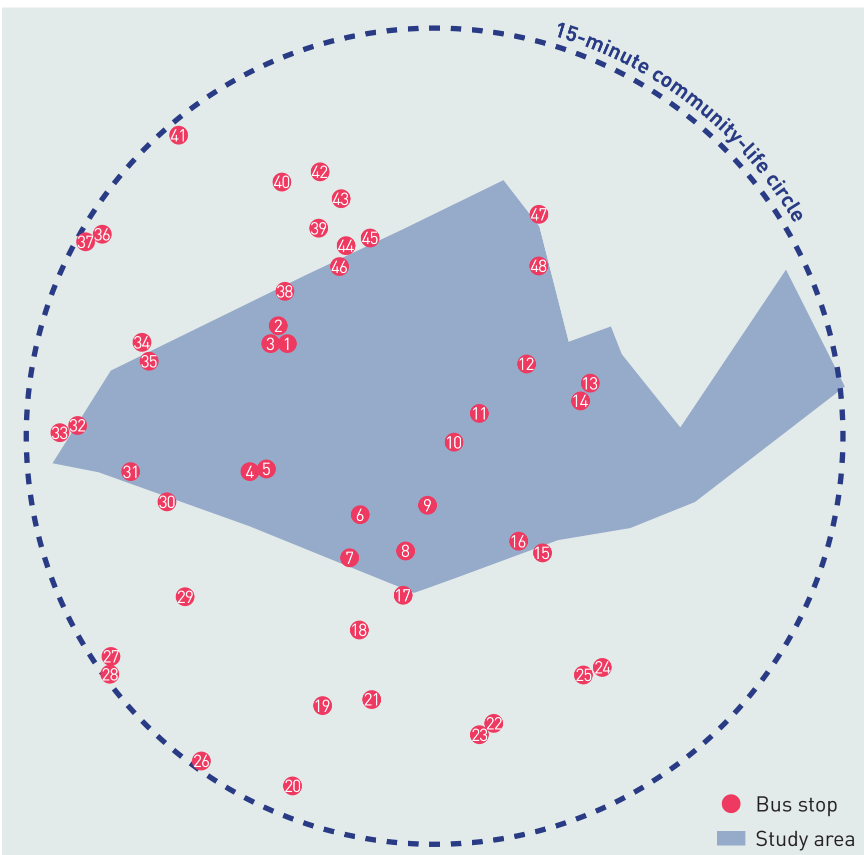
In October 2023, the research team conducted a survey of the current status of bus stop facilities within its "15-minute community-life circle" of the L Area in Shanghai[29].

3.1 Study Area

The L Area is located in Xujiahui Subdistrict, Xuhui District, covering a total area of approximately 26.5 hm^2. The L Area is representative for this research because it was designated as Shanghai's first batch of pilot projects for the "15-minute community-life circle" in 2022 and is one of the pilot community in the Xujiahui Subdistrict, with a construction goal of being livable, work-friendly, tourist-friendly, education-oriented, and elder-friendly. Moreover, through a series of environmental improvements including the optimization of bus stops, the L Area was announced as the first batch of national pilot "Complete Communities" in July 2023[30]. Its innovative development makes it a benchmark for inclusive community construction across the country.

3.2 Current Status and Issues of Bus Stop Facilities in the L Area

In terms of bus stop distribution, there were a total of 33 bus routes and 48 bus stops within the 15-minute community-life circle of the L area (Fig. 1). There were two types of bus stops, equipped with or without shelters (Fig. 2). Among them, 40 bus stops were equipped with shelters, seats, electronic displays and/or traditional signboards that provided information including stop name, bus routes, first and last bus time, fare, and advertisements. The other 8 bus stops were equipped without shelters, only with simple information signboards. The 48 bus stops were generally inadequate in long-distance recognition, the presence of audio announcement, and the provision of both guiding and warning tactile paving④ (Fig. 3). The criteria for evaluating the long-distance recognition of the bus stop were as follows: 1) bus stops without



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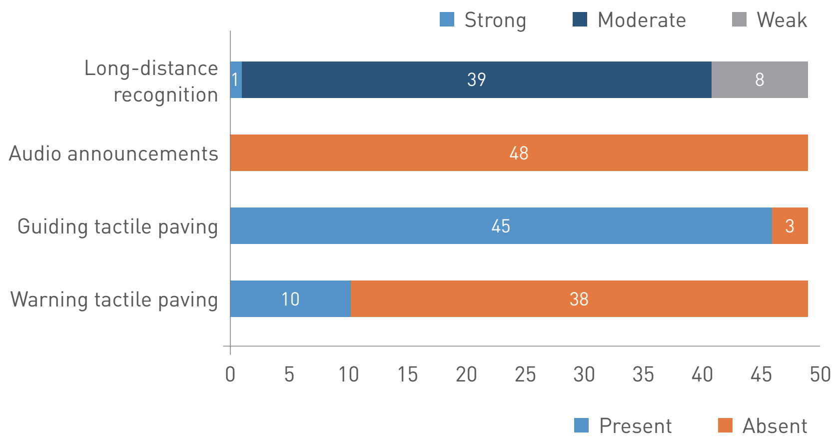
1. Bus stops within the 15-minute community-life circle in the L Area.
2. Bus stop with or without shelters.

④ According to the *Codes for Accessibility Design* (2012), the tactile paving for the visually impaired can be categorized into guidance tactile paving and warning tactile paving. Guidance tactile paving is strip-shaped and used to safely guide visually impaired passengers to the locations of accessible facilities; warning tactile paving, in the form of dot patterns, is placed at the starting and ending zones, as well as at turns, of the tactile paving, to alert visually impaired passengers that the spatial environment of the route ahead is going to change.



3 © Yubing Zheng, Dong Yao, Yibo Chen, Xiaoxi Zhao

3. Current status and issues of bus stop facilities in the L Area.

shelters physically occupy a relatively small area, making them difficult for visually impaired passengers to detect from a distance, they were therefore evaluated as "weak"; 2) bus stops with shelters generally occupy a larger area, making them moderate in long-distance recognition; 3) newly renovated bus stops with shelters exhibit strong long-distance recognition due to their bright and vivid colors.

4 Analysis of Daily Travel Needs of Visually Impaired Passengers

4.1 Respondents

There were 123 visually impaired individuals with disability certificates residing in the L Area⑤. From June to July 2023, as the pre-experiment, the research team interviewed 12 visually impaired individuals from the L Area to learn their difficulties in bus travels, so as to help identify the subsequent Kano questions.

In mid to late December 2023, the formal survey was taken place with the assistance of subdistrict and community staff. The team visited 53 visually impaired passengers and conducted Kano questionnaire interviews. These passengers were voluntary for the survey, representing 43.1% of the permanent visually impaired population in the area. A total of 53 valid questionnaires were collected, and the basic information of the respondents is presented in Table 2.

⑤ Data source: Xujiahui Subdistrict Office and Neighborhood Committees in the L Area.

Table 2: Basic information of the respondents

Item	Option	Quantity	Percentage
Gender	Male	16	30.2%
	Female	37	69.8%
Age	< 60	7	13.2%
	60 ~ 69	23	43.4%
	70 ~ 79	16	30.2%
	≥ 80	7	13.2%
Degree of visual impairment	Level 1	13	24.5%
	Level 2	16	30.2%
	Level 3	2	3.8%
	Level 4	22	41.5%
Age at onset of disability	< 20	18	34.0%
	20 ~ 39	7	13.2%
	40 ~ 59	13	24.5%
	≥ 60	15	28.3%
Duration of visual impairment (year)	< 20	24	45.3%
	20 ~ 39	10	18.9%
	40 ~ 59	13	24.5%
	≥ 60	6	11.3%
Household size	Living alone	8	15.1%
	2 ~ 3	39	73.6%
	Four or more	6	11.3%

4.2 Questionnaire Design and Validation

Usually, visually impaired passengers experience four stages during bus travel: traveling to the bus stop, arriving at the bus stop, waiting for the bus to arrive, and boarding and alighting the bus. According to the pre-experiment results, the actual challenges potentially faced by visually impaired passengers and their demands for improvement at each stage are summarized as Table 3. Correspondingly, their demands were summarized and categorized into three types—visual enhancement, auditory assistance, and spatial modification—and several secondary demands (Table 4) that were coded for subsequent importance grid analysis.

In this study, the Kano questionnaire contained seven paired sets of functional and dysfunctional questions (Table 5). In terms of the formal survey, the reliability coefficient (Cronbach's alpha) for the functional questions and dysfunctional questions both values exceed 0.7, indicating high reliability. In the validity test, a Kaiser-Meyer-Olkin (KMO) measure confirmed the appropriateness of factor analysis. The KMO values for the functional questions and dysfunctional questions were both greater than 0.6, indicating

Table 3: Challenges faced by visually impaired passengers during bus travel

Stage	Challenge	Demand
Traveling to the bus stop	Unable to locate the bus stop	Improving long-distance recognition
Arriving at the bus stop	Difficult to acquire information about bus stop names and bus routes served	Audio announcements for bus stop names; creating large-font bus stop signs
Waiting for the bus to arrive	Difficult to identify arriving bus numbers, distinguish buses arriving simultaneously, especially those behind the front bus; overcrowding on the platform	Audio announcements for bus arrivals; establishing an accessible boarding area
Boarding and alighting the bus	Unable to find the bus door; high bus steps	Audio announcements triggered by sensing the bus door; eliminating the vertical gap between the bus floor and the platform

Table 4: Demands of visually impaired passengers during bus travel

Demand type	Secondary demand	Description
A: Visual enhancement	A1: Improving long-distance recognition of bus stop	The bus stops are painted in bright colors, enabling visually impaired individuals to easily detect from a distance
	A2: Providing large-font bus stop signs	Enlarging the font size on bus stop signs, allowing visually impaired individuals to clearly read
B: Auditory assistance	B1: Audio announcements for the location of the bus stop	When approaching the bus stop, audio announcements for the stop name and the bus routes served
	B2: Audio announcements for bus arrivals	Audio announcements for upcoming bus arrivals
	B3: Audio announcements triggered by sensing the bus door	Assisting totally blind individuals in boarding the bus, audio announcements are made when they approach the bus door
C: Spatial modification	C1: Establishing an accessible boarding area	By designating specific areas, visually impaired individuals and other disabled persons are given priority when boarding
	C2: Eliminating the vertical gap between the bus floor and the platform	Lowing the bus floor or lifting boarding steps to assist visually impaired individuals and those with mobility impairments in boarding and alighting buses

Table 5: Functional questions and dysfunctional questions in the survey

Item	Functional question	Dysfunctional question	Response option
A1	How would you feel if bus stops were painted in bright colors (e.g., red, yellow) to enhance visibility from a distance?	How would you feel if bus stops were NOT painted in bright colors, making them harder to spot from a distance?	A. I like it that way B. It must be that way C. I am neutral D. I can live with it that way E. I dislike it that way
A2	How would you feel if bus stop signs adopted larger font sizes to improve readability?	How would you feel if bus stop signs maintained small font sizes that may compromise readability?	
B1	How would you feel if the bus stop provided automated voice announcements for the stop name when you approach it?	How would you feel if the bus stop DID NOT provide voice announcements, requiring visual confirmation of the stop name?	
B2	How would you feel if the bus stop provided voice announcements (e.g., "Bus XX is arriving") when buses approach?	How would you feel if the bus stop DID NOT provide arrival announcements, requiring manual checking of approaching buses?	
B3	How would you feel if an assistive device alerted you when approaching the boarding door of your target bus?	How would you feel if NO assistive device were available, requiring you to visually identify the boarding door by yourself?	
C1	How would you feel if an accessible boarding area were provided, where drivers prioritize assisting passengers with special needs?	How would you feel if NO accessible boarding area existed, requiring all passengers to board through standard entrances without priority assistance?	
C2	How would you feel if the bus deployed an access ramp or sloped pathway when you were boarding/alighting?	How would you feel if the bus DID NOT deploy any access ramp or sloped pathway, requiring you to navigate standard steps without assistance?	

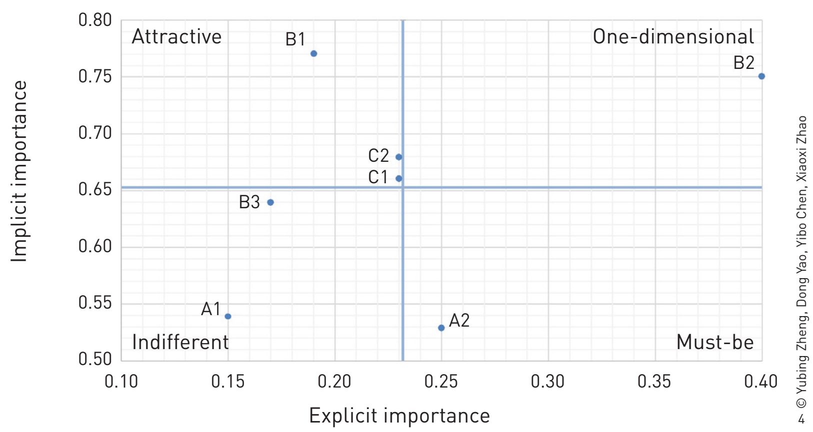
suitability for factor analysis. Moreover, the Bartlett's test of sphericity yielded a significance level of 0.000, which is less than 0.01. Based on the Kano data, explicit importance and implicit importance values were calculated to adjust the categorization results, which were then ranked according to their importance by the need hierarchy of must-be > one-dimensional > attractive > indifferent (Table 6, Fig. 4).

4.3 Analysis Results

According to the analysis results, must-be needs included

Table 6: Kano model-based classification of needs

Item	A (%)	O (%)	M (%)	I (%)	R (%)	Q (%)	Category	Implicit importance	Explicit importance	Adjusted category	Ranking
A1	37.74	15.09	0.00	45.28	0.00	1.89	I	0.54	0.15	I	7
A2	30.19	22.64	1.89	45.28	0.00	0.00	I	0.53	0.25	M	1
B1	60.38	16.98	1.89	20.75	0.00	0.00	A	0.77	0.19	A	3
B2	43.40	32.08	7.55	16.98	0.00	0.00	A	0.75	0.40	O	2
B3	49.06	15.09	1.89	33.96	0.00	0.00	A	0.64	0.17	I	6
C1	45.28	20.75	1.89	32.08	0.00	0.00	A	0.66	0.23	A	5
C2	49.06	18.87	3.77	28.30	0.00	0.00	A	0.68	0.23	A	4



4. The analysis result of the importance grid.

providing large-font bus stop signs (A2), while one-dimensional needs encompassed audio announcements for bus arrivals (B2). Attractive needs included audio announcements for the location of the bus stop (B1), eliminating the vertical gap between the bus floor and the platform (C2), and establishing an accessible boarding area (C1). Indifferent needs consisted of audio announcements triggered by sensing the bus door (B3) and improving long-distance recognition (A1). The importance ranking of each need was confirmed using two classification methods: by Kano need categories and by respondents' demand types (Table 7).

Notably, the need hierarchy for visually impaired-friendly bus stop facilities is influenced by the degree of visual impairment and the environmental features of the bus stop, with dynamic variations over time. On the one hand, from the perspective of the degree of visual impairment, typically only passengers with mild or moderate visual impairment are able to travel independently, as who can still recognize bus stop information from the signboards. Thus, large-font bus stop sign has the highest priority. For the same reason,

Table 7: Importance ranking of different Kano need categories and demands types

Classification	Ranking	Classification	Ranking
Must-be	A2	Visual enhancement	A2 > A1
One-dimensional	B2	Auditory assistance	B2 > B1 > B3
Attractive	B1 > C2 > C1	Spatial modification	C2 > C1
Indifferent	B3 > A1		

most visually impaired passengers can find the bus stops or bus doors, making the needs for improving long-distance recognition and audio announcements triggered by sensing the bus door indifferent.

On the other hand, from the perspective of the environmental features of the bus stop, audio announcements for bus arrivals were identified as one-dimensional needs, while audio announcements for the location of the bus stop as attractive needs. Both of these can be implemented by adding an audio module into existing electronic bus stop sign systems, without location limitations.

Attractive needs also included eliminating the vertical gap between the bus floor and the platform and establishing an accessible boarding area, both of which fall under spatial modification and are constrained by the bus stop space and the surrounding environment, which often involve the modification of multiple systems. The needs of visually impaired passengers also exhibit dynamic changes: in areas with a higher concentration of passengers with severe visual impairment or unfamiliar urban environments, indifferent needs may also become essential requirements.

4.4 Tailored Research

Different visually impaired passengers have varying needs for bus stop facilities, which are mainly influenced by factors such as age, degree of visual impairment, age at onset of disability, duration of visual impairment, and household size. Older passengers, those with a later age of onset, or those with a shorter duration of visual impairment were typically less familiar with the travel environment. Visually impaired passengers with a lower degree of impairment usually have better vision. Those with larger household sizes are more likely to receive assistance in travel, while visually impaired passengers living alone often face greater challenges relatively.

First, correlation analyses between must-be, one-dimensional, and attractive needs with respondents' demographic characteristics were conducted. With the exception of one-dimensional needs, the other two types of needs exhibited differentiated demographic characteristics (Table 8). For must-be needs, the demand for large-font bus stop signs was negatively correlated with the degree of visual impairment, indicating that passengers with mild visual impairments rely more on visual cues. In terms of attractive needs, the demand for audio announcements for the location of the bus stop was positively correlated with age and age at onset of disability, suggesting that elderly passengers and those with acquired visual impairments were more reliant on auditory assistance. The demand

Table 8: Correlation results between must-be and attractive needs and respondents' demographic characteristics

Need category	Item	Question type	Age	Degree of visual impairment	Age at onset of disability	Duration of visual impairment	Household size
Must-be	A2	Functional	—	−0.415**	—	—	—
Attractive	B1	Dysfunctional	−0.297*	—	−0.326*	—	—
	C2	Dysfunctional	−0.301*	—	−0.393**	0.320*	0.288*
	C1	Dysfunctional	—	—	—	—	0.321*

NOTES

1. ** means the significance at the 0.01 level (two-tailed) and * means the significance at the 0.05 level (two-tailed).
2. For the attractive needs, the merged analysis showed no significant results; therefore, item-by-item analysis was performed.

for eliminating the vertical gap between the bus floor and the platform was positively correlated with age and age at onset of disability, and negatively correlated with the duration of visual impairment and household size, highlighting the difficulties faced by elderly passengers, those with acquired visual impairments, and passengers living alone in terms of independent travel. The demand for establishing an accessible boarding area was negatively correlated with household size, further emphasizing the urgent needs of visually impaired passengers living alone.

Second, the correlation between respondents' demands and their demographic characteristics was analyzed (Table 9). The demand for visual enhancement was negatively correlated with the degree of visual impairment, highlighting the significant needs of passengers with mild visual impairments. The demand for auditory assistance was positively correlated with age and age at onset of disability, reflecting the unfulfilled needs of elderly passengers and those with acquired visual impairments. The demand for spatial modification was positively correlated with age and negatively correlated with household size, emphasizing the urgent needs of visually impaired passengers who live alone or are elderly.

5 Design Innovation

Based on the analysis results, the study proposed several design strategies for the L Area. The goal of constructing inclusive cities has led to the proposal of design strategies based on human–computer interaction. Design innovation primarily focuses on two aspects: facility upgrades and embodied technology. The former depends on the needs and characteristics of visually impaired passengers, as well as the type of bus stops; and the latter plays a critical role in developing assistive devices for visually impaired passengers.

5.1 Design Strategies Based on Human-Computer Interaction

From the perspective of the synergy between people, environment, and technology[31], the human-computer interaction (HCI) strategy should primarily adopt a visually impaired

Table 9: Correlation results between respondents' demands and their demographic characteristics

Demand type	Item	Question type	Age	Degree of visual impairment	Age at onset of disability	Duration of visual impairment	Household size
Visual enhancement	A1, A2	Functional	—	−0.318*	—	—	—
Auditory assistance	B1, B2, B3	Dysfunctional	−0.317*	—	−0.297*	—	—
Spatial modification	C1, C2	Dysfunctional	−0.271*	—	−0.318*	—	0.326*

NOTE

** means the significance at the 0.01 level (two-tailed) and * means the significance at the 0.05 level (two-tailed).

passenger-centered approach, while incorporating physical environment improvements such as enhanced bus stop facilities.

The optimization of bus stop facilities aims to eliminate the mobility barriers to visually impaired passengers' sensory perception on the travel environment by improving physical spaces and enhancing their ability to travel independently. The application of technology transforms the approach from purely engineering-oriented solutions (e.g., widening waiting areas and adding tactile paving) to comprehensive "engineering + technology" interventions. Ensuring the safe, independent travel of visually impaired individuals, the application of modern information technology can help create an environment conducive to the operation of smart devices with a dynamic service feedback loop, enabling forward-looking, intelligent solutions to address the actual, urgent issues in the daily travels of visually impaired passengers.

5.2 Problem-Oriented Enhancement of Bus Stop Facilities

Based on the findings in this study, phased optimization strategies for bus stops with or without shelters in the L Area were proposed by ensuring the rational allocation of resources and emphasizing the principle of "problem-oriented, step-by-step improvement." In the short term, the focus should be on meeting must-be needs; in the medium term, the emphasis should shift to improving one-dimensional needs; and in the long term, attractive needs should be addressed. These three phases correspond to the basic, enhanced, and advanced optimization versions. The research team proposed specific modifications for five key renovation options (Table 10).

For bus stops without shelters, as shown in Fig. 5, the basic optimization version focuses on providing large-font bus stop sign, which is easy to implement and has quick effect. This modification primarily serves passengers with lighter visual impairments. By optimizing factors such as text size, color contrast, and the layout of the bus stop sign, the long-distance recognition of the stop can be significantly improved.

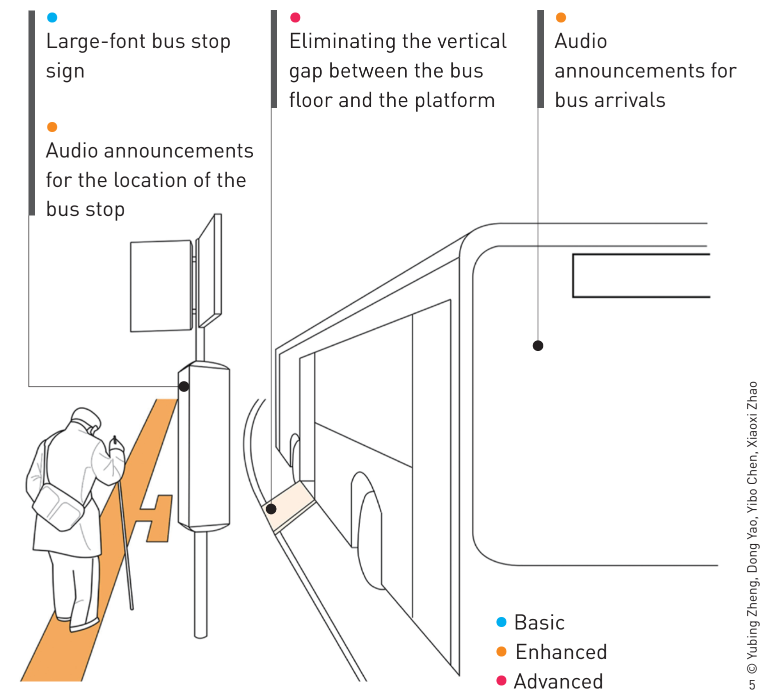
The enhanced optimization version introduces audio announcements for bus arrivals. Building upon existing electronic signage and bus systems, this can be achieved through simple interactive modifications to add voice prompt functionality. This enhancement not only benefits visually impaired passengers but also provides greater convenience for regular passengers.

The advanced optimization version further strengthens audio announcements for the location of the bus stop and the elimination of the vertical gap between the bus floor and the platform. The former can be integrated with measures of adding audio announcements for bus arrivals. The latter involves the

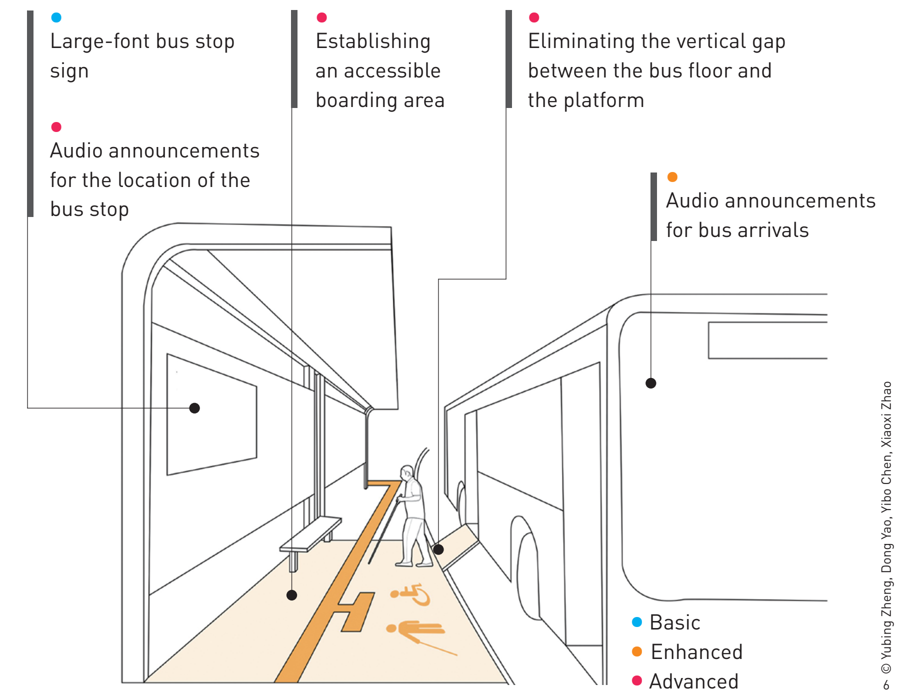
Table 10: Key points for improving bus stop facilities

Renovation option	Key point	Bus stop without shelter			Bus stop with shelter		
Large-font bus stop sign	Text height, font size, font selection, text and background color, character spacing, layout design, nighttime lighting	● (Basic)	● (Enhanced)	● (Advanced)	● (Basic)	● (Enhanced)	● (Advanced)
Audio announcements for bus arrivals	Base volume, volume adjustment under noise, nighttime volume control, speech rate, tone (male/female voice), announcement interval and frequency, content of the announcements, language versions (including dialect announcements), speaker installation height, spacing, and angle		● (Enhanced)	● (Advanced)		● (Enhanced)	● (Advanced)
Audio announcements for the location of the bus stop				● (Advanced)			● (Advanced)
Eliminating the vertical gap between the bus floor and the platform	Selection of transition devices (e.g., liftable steps, low-floor bus and boarding ramp), slope, width, anti-slip treatment, bus stopping position, warning signs, nighttime lighting, smart control system (automatic/manual activation)			● (Advanced)			● (Advanced)
Establishing an accessible boarding area	Position layout, area, ground marks, bus stopping position, nighttime lighting, assistance buttons, anti-slip treatment, waiting seats, shading and rain shelter, isolation guardrail						● (Advanced)

NOTE
● = Basic; ● = Enhanced; ● = Advanced.



5. Optimization strategies for bus stops without shelters.



6. Optimization strategies for bus stops with shelters.

collaborative design of buses and platforms, which is more complex and requires consideration of solutions such as low-floor buses and boarding ramps. Given the spatial limitations of bus stops without shelters, establishing accessible boarding areas is typically difficult, and therefore, is not included in the renovation options. However, with technological advancements, its feasibility can be reassessed in the future.

For bus stops with shelters, as shown in Fig. 6, usually offer ample physical space and better existing facilities, demonstrating significant advantages in the advanced optimization version. These bus stops provide greater modification potential and a higher passenger flow capacity, making them more conducive to comprehensive upgrades of accessible facilities. The advanced version should focus on establishing accessible boarding areas, further creating a more visually impaired-friendly environment.

For varied communities and bus stops, different renovation options should be adopted according to their specific conditions, including public health and visual health census. For example, adding audio announcements for bus arrivals are effective for all visually impaired passengers and without spatial limitations; if a community has a higher proportion of passengers with mild visual impairments, visual enhancement measures should be emphasized to improve the long-distance recognition of the stops, such as high-contrast colors and signage; if the community has a higher number of elderly passengers and those with acquired visual impairments, additional voice prompts and boarding assistance facilities should be introduced, such as audio announcements and liftable steps; or, if the community has a higher proportion of visually impaired passengers living alone, spatial modification facilities should be prioritized, such as establishing accessible boarding areas and employing low-floor buses.

5.3 Embodied Technology-Based Smart Assistive Devices

Embodied technology involves multiple disciplines⑥[32] and combines the sensory, motor, and cognitive mechanisms of the human body with technology to achieve interactive and collaborative integration between humans, the environment, and technology. To apply embodied technology, the travel environment for visually impaired passengers must incorporate innovations at the user end.

Based on the research findings, the research team has innovatively

⑥ "Embodied technology" is closely related to "embodied artificial intelligence." Artificial intelligence systems can directly engage with their surroundings. They use devices like sensors and monitors to compile data from their movements and environments, then apply machine learning, computer vision, and natural language processing to derive insights from that data, so as to adjust their decisions and actions over time (source: Ref. [32]).

developed a smart assistive device, Smart Cane (Fig. 7). Compared with a regular cane, the Smart Cane includes a power module, a help button, a prompt module (voice, vibration, etc.), and a reading module (RFID reader, Bluetooth receiver, etc.). Bus stop facilities (e.g., bus stop signs, tactile paving) are equipped with signal modules, which can interact with the reading module of the Smart Cane (Fig. 8).

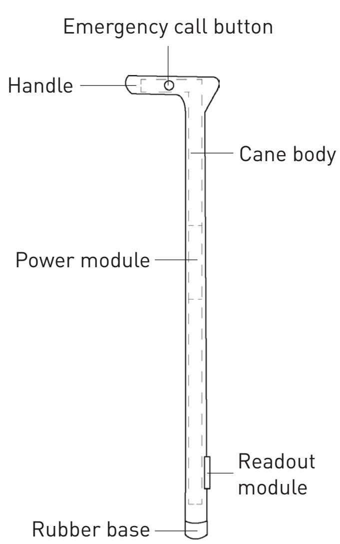
Through the interaction between the Smart Cane and bus stop facilities, multiple needs of visually impaired passengers can be addressed, supporting various smart travel scenarios. A core challenge faced by visually impaired passengers while waiting for the bus is the inability to accurately determine if their intended bus has arrived, particularly at bus stops served by multiple routes. Also, they often find it difficult to confirm whether they have heard the audio announcements in noisy street environments. By integrating RFID tags or signal modules into the bus stop signs to store bus stop names and route information, and installing RFID tags along the tactile paving at regular intervals to create a guiding system, the stop can become more navigable. Through real-time interaction between the reading module of the Smart Cane and the bus signal module, precise bus arrival notifications can be provided. When the reading module of the cane scans and identifies the signal of the target bus, the distance can be calculated based on signal strength, and a tiered reminder can be realized. For instance, when the bus enters a 30-m range of the bus stop, the signal module will continuously broadcast bus information (e.g., bus route, terminal); within a 15-m range, a short vibration prompt will be triggered to inform the visually impaired user that the bus is approaching; within a 5-m range, an audio announcement will be made (e.g., "Bus 26 is arriving") to ensure the individual can accurately identify the vehicle; and finally, when the bus arrives, the smart cane provides audio guidance to direct the passenger to the bus door.

In reality, visually impaired passengers typically require more time to board the bus. However, during peak hours, drivers may not notice them, leading to the bus doors closing prematurely. By linking the Smart Cane's help button with the bus system, the boarding process can be optimized. For example, when the visually impaired individual presses the help button, a priority boarding signal will be sent to the bus, triggering a notification to the driver. The onboard screen will display "visually impaired passenger boarding" and automatically extend the bus's stopping time. Additionally, the bus door anti-clamping mode can be activated to ensure the safety of the visually impaired passengers.

Currently, the embodied technology-based Smart Cane has already been patented, and in the future, it will contribute to the improvement of the travel environment for visually impaired passengers.

Visually impaired-friendly bus stops should adopt a comprehensive approach to ensure that accessible facilities fully address a variety of needs, providing more friendly accessible bus services. Through the aforementioned measures, it is possible to achieve comprehensive management of the needs of visually impaired passengers with different characteristics, thereby creating a safer and more convenient travel environment.

7. Smart Cane.
8. Interaction scenarios between the smart cane and the bus stop facility.



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6 Conclusions

This study systematically investigated the hierarchy of accessibility needs for bus stop facilities among visually impaired passengers using the Kano model. The empirical case study conducted in Shanghai's L Area revealed three distinct levels of needs: must-be needs (providing large-font bus stop signs), one-dimensional needs (audio announcements for bus arrivals), and attractive needs (audio announcements for bus stop locations, eliminating the vertical gap between bus floors and platforms, and establishing accessible boarding areas). Further analysis demonstrated statistically significant correlations between specific facility requirements and demographic characteristics (age, degree of visual impairment, etc.), providing empirical support for differentiated and phased optimization strategies. The embodied interaction system design integrating assistive device, Smart Canes, with bus stop facilities offers actionable solutions for creating inclusive transportation environments.

Besides, three methodological limitations should be acknowledged. First, due to the unique challenges of researching visually impaired populations, the sample representativeness and the balancing of key variables including gender, degree of visual impairment, etc. could be improved (n = 53, coverage rate 43.1%). Second, the geographical limitation to L Area necessitates further validation of findings in other community contexts. Third, the Smart Cane prototype requires field testing to verify its technical feasibility and user acceptance.

The advancement of smart and digital accessibility solutions holds significant potential for enhancing visually impaired-friendly bus stop development. However, it faces challenges including research costs and user acceptance. Future research can explore more on the following directions: 1) expanding sample diversity to encompass broader demographics of visually impaired individuals across various community settings; 2) advancing intelligent technology applications through cost-effective, high-availability solutions; and 3) fostering policy-technology synergy to establish institutional frameworks for universal accessibility implementation. These advancements will serve as a powerful catalyst for promoting social equity and enhancing human well-being.

ELECTRONIC SUPPLEMENTARY MATERIAL

Supplementary material is available in the online version of this article at https://doi.org/10.15302/J-LAF-1-020112.

Competing interests | The authors declare that they have no competing interests.

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基于Kano模型的视障友好型公交站设施需求研究与设计创新

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摘要

公交车站是现代城市的重要基础设施，但目前仍缺少针对视障人群的公交站无障碍设施研究。本文以上海市L片区为例展开调研，结果表明，其“15分钟社区生活圈”内的公交站点在可识别性、无障碍设施配置等方面存在较明显不足。利用Kano模型对视障残疾人的需求分类排序，研究发现，大字号站牌属于基本型需求，公交车到站语音提示属于期望型需求，公交车站语音提示、消除公交车地面与站台高差、独立的无障碍上车区属于魅力型需求。定制研究表明，不同特征的视障人群对于公交车站无障碍设施的需求有所区别，主要体现在年龄、视障等级、致残年龄、视障时长，以及家庭人口规模等方面。在此基础上，本研究以问题为导向，针对不同类型的车站提出分阶段设施提升策略，短期聚焦基本型需求，中期提升期望型功能，远期实现魅力型创新，分别对应基础版、增强版和高级版车站改造措施。随后，研究探索了基于具身技术的智能盲杖与车站设施交互的创新构想，以此回应视障者的多项需求，构建多种智慧乘车场景。

关键词

公交站设施；视障友好；无障碍；Kano模型；具身技术；包容性城市

文章亮点

- 使用Kano模型调查视障人群对公交站无障碍设施的需求
- 以问题为导向，针对不同类型车站提出分阶段设施提升措施
- 基于具身技术，研发盲杖这一可支持视障人群公交出行的智能辅具

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