Research on Age-Friendly Design of In-Vehicle Human-Machine Interface Based on Kano-AHP Model—Focusing on the Elderly Driver Group

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Abstract. The in-vehicle human-machine interface (HMI) plays a crucial role in driving safety and operational experience. However, existing designs mainly target young users and fail to fully consider the actual needs of the elderly group. This study takes elderly drivers as the research object, adopts a combined method of Kano model and Analytic Hierarchy Process (AHP) to construct an analysis framework for demand identification and priority ranking. After establishing a demand pool through literature review and interviews, the Kano model is used for attribute classification, and AHP is combined to calculate demand weights. The results show that the primary needs of elderly drivers focus on safety-related functions and simplified operation processes, among which functions such as emergency braking assistance, voice correction, and fatigue monitoring have the highest priority; demands such as adjustable font size, haptic feedback, and voice interaction play an important role in reducing cognitive burden and optimizing experience. Based on this, the study proposes core design strategies of "safety first, simple operation, clear presentation, multimodal support, and emotional care". The contribution of this research lies in the first systematic application of the Kano-AHP model in the age-friendly design of in-vehicle HMI, proposing a comprehensive method that combines qualitative and quantitative analysis, and providing empirically based design suggestions. The results not only expand the theoretical dimension of age-friendly design research but also provide practical references for the intelligent automobile industry to address the aging challenge.

Keywords: age-friendly design, in-vehicle human-machine interface, elderly drivers, Kano model, AHP

1. Introduction

The global population structure is irreversibly aging, and Chinese society is undergoing profound transformation. Data from the National Bureau of Statistics shows that the population aged 60 and above in China has reached 296 million, accounting for 21.1% of the total population, indicating a significant aging trend [1]. Against this background, the "silver-haired driver" group is gradually expanding. Improved living standards and extended healthy life expectancy have enabled more elderly people to maintain good driving ability and travel needs. Meanwhile, automobiles are rapidly moving towards intelligence and connectivity, with in-vehicle human-machine interface (HMI) functions becoming increasingly complex, and interaction methods shifting from traditional physical buttons to multimodal interaction dominated by touch screens and voice.

There is a significant contradiction between this technological evolution and the physiological and cognitive characteristics of elderly drivers. Elderly users generally face problems such as decreased eyesight, slowed information processing speed, reduced short-term memory capacity, and learning anxiety about complex new technologies [2]. Existing in-vehicle HMI designs are mostly centered on young and technologically proficient users, emphasizing functional diversification and visual technological sense, while rarely considering the actual needs of the elderly driving group. During use, the elderly may encounter difficulties such as unrecognizable interface information, cumbersome operation steps, and increased risk of false touches, which not only affect driving experience and confidence but also pose potential traffic safety hazards.

Scientifically identifying the core needs of elderly drivers in terms of in-vehicle HMI and converting them into age-friendly design strategies with clear priorities and strong feasibility has become an important issue urgently to be solved in the fields of industrial design and human-computer interaction.

2. Prolegomenon

2.1. Research status

2.1.1. Research on age-friendly design

The in-vehicle human-machine interface (HMI) plays a crucial role in driving safety and operational experience, but existing designs mainly target young users and fail to fully consider the actual needs of the elderly group.

This study takes elderly drivers as the research object, adopts a combined method of Kano model and Analytic Hierarchy Process (AHP) to construct an analysis framework for demand identification and priority ranking. After establishing a demand pool through literature review and interviews, the Kano model is used for attribute classification, and AHP is combined to calculate demand weights.

The results show that the primary needs of elderly drivers focus on safety-related functions and simplified operation processes, among which functions such as emergency braking assistance, voice correction, and fatigue monitoring have the highest priority. Demands such as adjustable font size, haptic feedback, and voice interaction play an important role in reducing cognitive burden and optimizing experience. Based on this, the study proposes core design strategies of "safety first, simple operation, clear presentation, multimodal support, and emotional care".

The contribution of this research is the first systematic application of the Kano-AHP model in the age-friendly design of in-vehicle HMI, proposing a comprehensive method that combines qualitative and quantitative analysis and providing empirically based design suggestions. The results not only expand the theoretical dimension of age-friendly design research but also provide practical references for the intelligent automobile industry to address the aging challenge.

2.1.2. Research on in-vehicle HMI design

The in-vehicle human-machine interface (HMI) is the core of interaction between drivers and vehicle information systems, and its design has always been the focus of academic and industrial attention. Current research mainly focuses on user experience, driving safety, and multimodal interaction (touch, voice, gesture, etc.) [3]. Existing studies have shown that unreasonable HMI design can significantly increase drivers' cognitive load and distract attention. Some studies have paid attention to differences among different age groups, but research that systematically integrates age-friendly concepts into the HMI design process and provides quantitative basis is still relatively lacking.

2.1.3. Application research of Kano model and AHP method

The Kano model can distinguish user demand attributes (basic, expected, attractive) and reveal the nonlinear relationship between product functions and user satisfaction. As a multi-criteria decision-making tool, the Analytic Hierarchy Process (AHP) can quantify qualitative issues through pairwise comparison and calculate weights to determine demand priorities. The combination of Kano and AHP has been applied in fields such as smart homes, health-related applications, and baby products, and its practical value in identifying user needs and guiding design has been proven. However, its application in in-vehicle HMI, especially in age-friendly research for the elderly driving group, is still in the exploration stage, leaving room for further research.

In summary, although existing research has accumulated a large number of achievements in age-friendly design principles, in-vehicle HMI, and the application of Kano-AHP methods, there are still deficiencies:

Research on age-friendly interaction for driving, a high-risk scenario, is not in-depth enough;

In-vehicle HMI design lacks systematic and quantitative analysis of the needs of elderly users;

The application of the Kano-AHP paradigm in the age-friendly design of in-vehicle HMI is still in its initial stage.

Therefore, this study aims to make up for the above deficiencies. By introducing the Kano-AHP model, it proposes a scientific methodology and practical path from demand identification to priority ranking, providing a reference for the age-friendly design of in-vehicle HMI for the elderly driving group.

2.2. Research content, methods and technical route

2.2.1. Research content

This study mainly includes:

Analyzing the physiological, cognitive, and behavioral characteristics of elderly drivers and their needs in in-vehicle HMI interaction;

Establishing an age-friendly design demand pool for elderly drivers through interviews and literature research;

Classifying and screening demands using Kano model questionnaires to identify key demands;

Constructing a demand hierarchical structure model, calculating the weight of each demand using AHP to clarify priorities;

Finally, proposing targeted age-friendly HMI design strategies based on experimental results.

2.2.2. Research methods

The research methods include:

Literature research method: Systematically combing theories and research related to age-friendly design, in-vehicle HMI, and Kano-AHP;

User interview method: Exploring the pain points and expectations of elderly drivers in HMI use through semi-structured interviews;

Questionnaire survey method: Designing and distributing Kano and AHP questionnaires to collect data required for classification and weight analysis;

Quantitative analysis method: Using Kano and AHP methods to process data to realize qualitative classification and quantitative ranking of demands.

3. User research and analysis

3.1. Analysis of physiological and cognitive characteristics of the elderly driving group

As Chinese society enters a stage of deep aging, the elderly driving group has gradually become a special group that cannot be ignored. According to data from the Traffic Management Bureau of the Ministry of Public Security, the number of drivers aged 60 and above holding driver's licenses has been continuously increasing in recent years [4]. Automobiles are not only an important means of daily travel for the elderly but also a key tool to maintain their social participation and life independence [5]. However, changes in the physiological, cognitive, and psychological aspects brought about by aging have a significant impact on the user experience and safety of the in-vehicle human-machine interface (HMI) [6].

3.1.1. Physiological characteristics and their impacts

1. Decline in Visual Acuity

With age, problems such as presbyopia, cataracts, and glaucoma are common among the elderly [7]. Its direct manifestations are:

Decreased visual acuity: Making it difficult for them to quickly identify small fonts, complex icons, or low-contrast information on the screen [8].

Sensitivity to glare: In nighttime or strong light environments, excessive screen brightness or reflection may cause visual discomfort and reduce information reading efficiency [9].

Narrowed visual field: The ability to capture peripheral information while driving is reduced, making them more dependent on concise and intuitive information presentation in HMI.

2. Hearing Loss

Hearing decline with age is manifested as reduced sensitivity to high-frequency sounds and decreased speech recognition ability, especially in the driving environment with engine noise and road noise. This directly affects the reception efficiency of elderly users for in-vehicle voice prompts or navigation broadcasts [10], which may lead to missing key information.

Therefore, the voice design of HMI needs to balance adjustable volume, moderate speech rate, and high voice clarity, and allow users to freely switch or combine between visual and auditory modes.

3. Reduced Physical Flexibility

Elderly people often show decreased joint flexibility and muscle strength, which makes it easy for them to feel strenuous when performing complex or rapid operations [11]. For example, frequently switching hands between the steering wheel and the central control screen, or needing to accurately click on small touch areas, will increase their operation difficulty and driving burden.

Therefore, the age-friendly design of HMI should reduce high-frequency complex operations and increase "one-key" functions and large-area touch areas.

4. Slowed Reaction Speed

Slowed nervous system response makes elderly drivers show a certain delay in information perception, decision-making, and action execution [12]. In emergency situations, this delay may directly increase traffic risks.

Therefore, the in-vehicle system must ensure a concise interaction process, timely and clear prompts, and avoid users falling into lengthy interface switching or cumbersome operation steps.

3.1.2. Cognitive characteristics and their impacts

1. Weakened Ability to Learn New Things

Elderly people often have a high learning cost when accepting and mastering emerging technologies (such as intelligent voice, intelligent navigation, multi-screen interaction). They prefer "intuitive and highly analogous" operation modes rather than frequently reading instructions or making repeated attempts.

Therefore, HMI needs to emphasize the consistency of operation logic and avoid strangeness caused by excessive innovation [13].

2. Impaired Short-Term Memory

In a multi-tasking driving environment, elderly people are prone to forgetting navigation information or operation prompts just obtained. For example, the system prompts "turn left in 200 meters", but the user may forget due to distraction [14], leading to missing the instruction.

This requires HMI to present key information in a "timely, repeated, and redundant" manner, such as combining visual prompts, voice broadcasts, and path highlighting to ensure that information is not missed.

3. Reduced Information Processing Capacity

When facing complex interfaces, elderly users may feel confused due to information overload and find it difficult to make decisions quickly. This puts forward the requirement of "reducing cognitive burden" for the design of in-vehicle HMI, that is, the information organization and interface layout must be concise, hierarchical, and logically clear [15].

3.1.3. Psychological characteristics and their impacts

1. Fear of Difficulty

Elderly users often have anxiety and rejection towards complex technologies. Too many new functions and high-degree-of-freedom operations make them feel anxious instead. This psychological factor directly affects their willingness to use the in-vehicle system [16].

2. Desire for Independent Driving

Despite aging limitations, the elderly generally desire to maintain travel independence and autonomy. Driving behavior and vehicle use are important symbols of their social participation [17]. Therefore, they have a higher acceptance of "assistive rather than substitutive" designs, that is, they hope technology provides help but do not want to be completely deprived of driving rights [18].

Comprehensively, the physiological, cognitive, and psychological characteristics of the elderly driving group jointly determine that the age-friendly design of in-vehicle HMI must follow the basic principles of simplicity and intuition, strong fault tolerance, multimodal redundancy, and emotional care.

3.2. Construction of age-friendly design demand pool for in-vehicle HMI

To systematically identify the interaction needs of the elderly driving group, this study adopts a combined method of "literature analysis + user interviews" to gradually construct a comprehensive list of age-friendly design demands.

3.2.1. Literature analysis

On the basis of the first part of the literature review, combined with domestic and foreign research results on age-friendly interaction design, the following categories of design principles and demands that are particularly important for the elderly can be summarized:

1. Interface Visualization and Readability

Adjustable font size, avoiding small fonts and low contrast [19];

Icons with high recognition, avoiding abstract symbols [20];

Concise display content, avoiding presenting too much information at one time [21].

2. Operational Convenience and Low Load

Sufficiently large touch areas to reduce false operations.

Providing one-key access to commonly used functions, such as one-key navigation and one-key help.

Consistent operation logic to reduce learning burden [22].

3. Multimodal Interaction Support

Providing voice control to reduce the need for manual operations.

Voice broadcasts need to be clear and adjustable, avoiding lengthiness.

Allowing users to flexibly choose between visual, auditory, and tactile modes [23].

4. Safety and Risk Prevention and Control

Clear and redundant system prompts, such as navigation providing both visual highlighting and voice reminders.

Providing fault tolerance and confirmation mechanisms for key operations to avoid risks caused by false touches [24].

5. Emotional and Social Care

The system should reflect a sense of care, such as regular rest reminders and health monitoring linkage.

The voice interaction style should be friendly rather than indifferent to avoid increasing psychological alienation [25].

Through sorting out relevant literature, a preliminary demand framework can be formed. However, relying solely on literature is difficult to reflect the actual pain points of local elderly drivers, so it is necessary to supplement with user interviews.

3.2.2. User interviews

To make up for the deficiencies of literature analysis, this study also conducted exploratory research on some elderly drivers through semi-structured interviews, focusing on their interaction pain points and improvement expectations in daily driving. Overall, the interviewees generally mentioned insufficient recognition of fonts and icons, unstable voice recognition experience, deep menu levels, and difficulty in completing complex operations in high-pressure driving environments. At the same time, they showed high expectations for safety and care functions such as health reminders and emergency calls.

3.2.3. Formation and transition of preliminary demand pool

Comprehensive literature analysis and user interviews can summarize a preliminary age-friendly design demand pool, covering dimensions such as information presentation, operation interaction, multimodal support, safety assistance, and emotional care. The demand pool at this stage is still in the exploration and summary level, and its value lies in providing candidate indicators for subsequent model-based research. In the third part, based on this demand pool, the study will use the Kano model to classify demand attributes, and further combine the AHP method to rank the priorities of key demands, thereby forming a more operable basis for design optimization.

4. Demand modeling and design optimization based on Kano-AHP

4.1. Kano model

As a classic tool for user demand classification, the core value of the Kano model lies in revealing the nonlinear relationship between product function attributes and user satisfaction. Proposed by Japanese scholar Noriaki Kano in 1984, the model scientifically classifies user demands into five categories through designing positive and negative two-way questionnaires, such as "how do you feel if the product has this function" and "how do you feel if the product does not have this function": Must-be Quality (M): Refers to the basic functions that the product must satisfy; lack of them will lead to strong dissatisfaction, such as car seat belt alarm; One-dimensional Quality (O): Has a linear correlation with satisfaction, such as the improvement of navigation system accuracy; Attractive Quality (A): Is an innovative design that exceeds user expectations and can significantly improve satisfaction, such as in-vehicle intelligent health monitoring; Indifferent Quality (I): Has no substantial impact on user experience; Reverse Quality (R): Causes user resistance [26].

The research steps mainly include: (1) Constructing an initial demand pool; (2) Designing and distributing Kano two-factor questionnaires; (3) Collecting data and classifying demand attributes; (4) Calculating Better-Worse coefficients for quantitative analysis.

In the field of age-friendly design, the Kano model can effectively identify the real demands of elderly users. Cui Zixi's research on the elderly home medical system shows that through the coefficient calculation formula of Better-Worse [27]:

$$\text{Better}=(\text{A}+\text{O})/(\text{A}+\text{O}+\text{M}+\text{I}) \ \text{Worse}=(\text{O}+\text{M})/(\text{A}+\text{O}+\text{M}+\text{I})$$

Among them, the "emergency call function" (Better=0.42, Worse=0.38) was classified as a must-be quality, while the "traditional Chinese medicine health preservation service" (Better=0.51, Worse=0.29) belonged to the attractive quality. This classification provided an accurate basis for enterprise resource allocation. It is worth noting that the traditional Kano model has limitations—it cannot quantify the priority differences of demands in the same category. For example, in the design of automobile interfaces, which is more important between "collision warning" and "lane keeping", both of which are must-be qualities, a more refined decision-making tool is needed [28].

4.2. AHP method

The Analytic Hierarchy Process (AHP) is an effective means to solve such problems. Founded by American operations researcher Thomas L. Saaty in 1980, it constructs a hierarchical structure model of "target layer - criterion layer - scheme layer", uses the 1-9 scale method for pairwise comparison of factors, and finally calculates the weight of each element [29]. Li Runying used AHP to rank the weights of 21 demands screened by Kano in the functional design of community elderly care APP. The results showed that the importance of "medical consultation" was 6.3 times that of "community activities". This conclusion guided the team to invest 70% of the development resources into the core medical module [30]. The scientificity of AHP relies on strict consistency test (Consistency Ratio, CR<0.1). Hu Zhe constructed a judgment matrix in the research of automobile HMI, calculated the maximum eigenvalue λmax, and finally verified that CR=0.058<0.1, ensuring the reliability of the weight results [31].

This study adopts the Kano-AHP hybrid model that integrates the advantages of both: the first stage uses Kano to qualitatively filter invalid demands, and the second stage uses AHP to quantitatively rank the remaining demands. For example, Kang Yuanjing applied this model in the design of growth-oriented baby dining chairs, increasing the product user satisfaction to 4.2/5 points, which verified the effectiveness of the method [32]. This model is especially suitable for heterogeneous groups such as elderly drivers, and can solve multi-objective conflict problems such as "safety demand" and "operational simplicity" [33].

4.3. Extraction of multimodal interface design attributes

The initial attribute pool in this study was constructed using a mixed research method. First, through bibliometric analysis, 32 studies on age-friendly in-vehicle interaction included in CNKI from 2019 to 2024 were retrieved, and high-frequency design elements were extracted as shown in Figure 3.1.

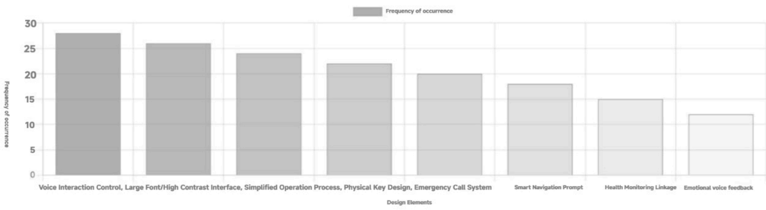

Figure 1. Extraction of high-frequency design elements

Subsequently, some elderly drivers around were contacted for in-depth interviews. A total of 14 drivers aged 65-75 (male-female ratio 1:1, driving experience ≥10 years) were recruited for this study. The situational recall method was used to guide the description of driving pain points. Typical feedback included: "The screen reflection made it impossible to see the navigation clearly when driving on the highway on a rainy night" (visual), "The navigation voice was covered by the air conditioner wind" (auditory), "The touch screen buttons were too small and I always clicked the wrong one" (tactile). The interview texts were coded and analyzed by Nvivo12, and a total of 146 original demand statements were extracted. Some interview texts are listed as follows:

Table 1. In-depth interview table

ID	Gender	Driving Scenario	Original Statement
P01	Male	Rainy night highway	When driving on the highway on a rainy night, the reflection of the central control screen was like a mirror, and the navigation route was completely invisible. I almost missed the exit. I had to stretch my neck to look closely, which was too dangerous.

Table 1. (continued)

P04	Female	Urban expressway	When the air conditioner was turned on at high speed, half of the navigation voice was covered by the wind. I couldn't hear whether it was "turn left" or "turn right", so I had to turn off the air conditioner, and ended up sweating a lot.
P07	Male	Toll station	The touch payment button was smaller than a fingernail! I couldn't click it accurately even with reading glasses. The cars behind were honking wildly, and my hands shook even more...
P09	Female	Tunnel	When entering and exiting the tunnel, the light changed suddenly, and the screen turned completely white. By the time it automatically adjusted the brightness, I was almost hitting the wall!
P12	Male	Heavy rain	The voice assistant suddenly broadcast the news, covering the navigation prompt. I shouted "shut up" three times before it stopped, and I almost drove off the elevated ramp.
P14	Female	Night parking lot	The radar alarm sound was too sharp when reversing, which scared my heart racing. I wanted to turn down the volume, but accidentally turned on the radio...

4.4. Demand attribute classification based on Kano model

4.4.1. Questionnaire design and data collection

Based on the 22 initial demands for age-friendly design of in-vehicle HMI formed in the previous research (see Table 3.2), this study designed a Kano questionnaire. For each demand, the questionnaire set two positive and negative questions: "How do you feel if the in-vehicle system has this function?" and "How do you feel if the in-vehicle system does not have this function?". Each question adopted a 5-point Likert scale with options: "Like very much", "Should be so", "Indifferent", "Reluctantly accept", "Dislike".

The questionnaires were mainly distributed to users aged 60 and above with driving experience through channels such as offline community elderly activity centers and elderly student groups in driving schools. A total of 250 questionnaires were distributed, and 235 valid questionnaires were recovered, with an effective recovery rate of 94%.

4.4.2. Data analysis and demand attribute classification

The collected data were analyzed according to the Kano model evaluation table, the distribution frequency of each demand item in the five attributes was counted, and the final attribute category was determined according to the maximum frequency principle. The attribute classification results of some core demand items are shown in Table 3.2.

Table 2. Kano attribute classification results of age-friendly design demands for in-vehicle HMI (partial)

Demand Category	No.	Demand Indicator	M	O	A	I	R	Total	Attribute Classification	Better	Worse
Basic Functions	C1	One-key login/startup	45	90	70	30	0	235	O	0.68	0.57
	C2	Seamless identity verification	30	50	125	30	0	235	A	0.74	0.34
	C3	My health status	25	40	100	70	0	235	A	0.60	0.28

Table 2. (continued)

Demand Category	No.	Demand Indicator	M	O	A	I	R	Total	Attribute Classification	Better	Worse
	C4	Key information reminder	110	75	35	15	0	235	M	0.47	0.79
	C5	Full-scenario voice assistant	40	65	105	25	0	235	A	0.72	0.45
	C6	Vehicle status at a glance	95	80	40	20	0	235	M	0.51	0.74
	C7	Trip recording and review	35	55	90	55	0	235	A	0.62	0.38
	C8	One-key call to emergency contacts	130	60	30	15	0	235	M	0.41	0.81
	C9	One-key navigation to frequently used destinations	50	85	75	25	0	235	O	0.68	0.57
Visual Presentation	C10	Adjustable font size	120	65	35	15	0	235	M	0.43	0.79
	C11	Clear and readable font type	40	70	80	45	0	235	O	0.64	0.47
	C12	Emphasized contrast colors	55	90	65	25	0	235	O	0.66	0.62
	C13	Appropriate color saturation	50	75	80	30	0	235	O	0.66	0.53
	C14	Icons mainly based on physical images	35	60	110	30	0	235	A	0.72	0.40
	C15	Clear division of information layout	60	95	60	20	0	235	O	0.66	0.66
Interaction Method	C16	One-key operation/shortcut entrance	105	70	45	15	0	235	M	0.52	0.74
	C17	Options take precedence over input	70	85	60	20	0	235	O	0.62	0.66
	C18	Voice input instead of typing	30	55	120	30	0	235	A	0.74	0.36
Demand Category	No.	Demand Indicator	M	O	A	I	R	Total	Attribute Classification	Better	Worse
	C19	Enlarged operation hot zone	80	75	60	20	0	235	O	0.58	0.66
	C20	Simple and easy-to-use operation process	115	60	40	20	0	235	M	0.43	0.74
	C21	Easy-to-understand feedback	90	75	50	20	0	235	M	0.53	0.70
	C22	Functional modularization/scenario-based	40	65	100	30	0	235	A	0.70	0.45

According to the classification results, the study selected 5 Must-be Qualities (M), 11 One-dimensional Qualities (O), and 6 Attractive Qualities (A). Indifferent Qualities (I) and Reverse Qualities (R) were not included in the main categories in this study, so they were not considered in the subsequent analysis. The selected 22 key demands were used as the basis for AHP analysis.

To further quantify the demand priority, the satisfaction coefficient (Better/SI) and dissatisfaction coefficient (Worse/DSI) of each demand were calculated. The calculation formulas are as follows:

$$\text{Better} = (A + O)/(A + O + M + I), \text{Worse}=1(O+M)/(A+O+M+I)$$

This study strictly screened the functional demands of the multimodal interface for elderly drivers through the Kano model to focus on the core demands with the most optimization value. The screening process followed clear quantitative standards and attribute characteristic analysis. Specifically, this study identified and included 9 high-impact functional demands for subsequent in-depth analysis. The screening basis for these demands is their significant "Better" coefficient and attribute classification. According to the Kano attribute classification, these 9 demands are further subdivided into: 5 are classified as Must-be Qualities, meaning their realization is the basic function that users consider the product or service should have, and failure to meet them will lead to strong dissatisfaction; 1 is classified as One-dimensional Quality, which has a linear correlation with satisfaction; 3 are classified as Attractive Qualities, representing innovative or surprising functions that exceed user expectations and can significantly improve satisfaction.

At the same time, this study clearly excluded demand items with Indifferent Qualities and Reverse Qualities to avoid resource waste and focus on key optimization points.

Based on the above screening results, this study constructed a structured three-level demand evaluation system, aiming to provide a clear framework for subsequent interface optimization decisions. The target layer of the system is clearly set as the ultimate goal of "multimodal interface optimization for elderly drivers". The criterion layer is divided into two core evaluation dimensions: "Must-be Qualities" representing the safety baseline and "Attractive Qualities" representing experience value-added, according to the core attribute classification of the Kano model. Among them, B1 category demands are directly related to the core functions of driving safety and have non-negotiability; B2 category demands focus on improving the comfort and personalized experience of human-computer interaction [34].

4.5. Demand weight calculation based on AHP model

To scientifically quantify the relative importance of various age-friendly demands in interface optimization, this study adopted the Analytic Hierarchy Process (AHP) to calculate demand weights. The AHP method can effectively handle multi-criteria decision-making problems through steps such as constructing a hierarchical structure model, constructing a judgment matrix, calculating weight vectors, and consistency testing.

It is particularly suitable for scenarios where qualitative judgments are converted into quantitative analysis. Its core lies in pairwise comparison of factors by experts with respect to a certain criterion in the upper level, establishing a judgment matrix, and then calculating the relative weight of each element.

4.5.1. Construction of hierarchical model

Based on the 9 key demands screened by the Kano model, this study constructed a three-level hierarchical structure model [35]. The target layer is clearly defined as the ultimate goal of "multimodal interface optimization for elderly drivers". The criterion layer is divided into two dimensions: "Must-be Qualities (B1)" representing the safety baseline and "Attractive Qualities (B2)" representing experience value-added, according to the demand attribute classification theory. Among them, B1 category demands are directly related to the core functions of driving safety and have non-negotiability; B2 category demands focus on improving the comfort and personalized experience of human-computer interaction [36].

In the design of the indicator layer, the study refined the criterion layer into 9 operable design indicators: under the B1 criterion, five safety functions are deployed: emergency braking assistance

(C1), voice correction (C2), fatigue monitoring (C3), haptic warning (C4), and one-key operation/shortcut entrance (C5); under the B2 criterion, four experience optimization functions are set: ARHUD (C6), voice assistant (C7), adjustable font size (C8), and icons mainly based on physical images (C9). This hierarchical model clearly presents the logical transmission path between design goals, functional attributes, and specific design elements through a tree structure [37].

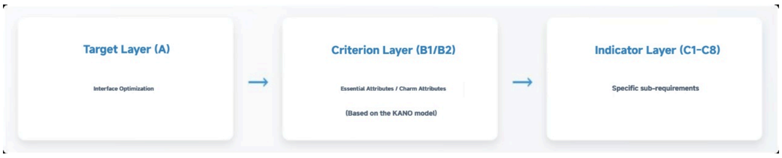

Figure 2. Three-level hierarchical structure model

4.5.2. Construction of judgment matrix and weight calculation

In this study, the weight calculation process of AHP realized the quantification of demand priority through a rigorous mathematical framework [39]. This study invited 12 interdisciplinary experts, including ergonomics professors, interaction designers, geriatrics experts, and driving instructors, to conduct pairwise importance comparison of elements mainly using the Saaty 1-9 scale method. The core process starts with the construction of the judgment matrix: in the comparison of the criterion layer between Must-be Qualities and Attractive Qualities, expert feedback statistics show that 7 people judged B1 as "obviously more important" than B2, and 5 people judged it as "strongly more important". The relative importance value aB1B2=5.83 was obtained through weighted average calculation, and the scale value was rounded to 6 according to AHP specifications, forming the criterion layer judgment matrix: the weight vector was calculated for this matrix using the sum-product method. First, column normalization was performed to obtain the normalized matrix, and then row summation was performed to get WB1Pre=1.7142 and WB2Pre=0.2858.

$$\mathbf{A} = \begin{bmatrix} 1 & 6 \\ 1/6 & 1 \end{bmatrix}$$

Finally, normalized processing derived the criterion layer weights wB1=0.857 and wB2=0.143. The result passed the consistency test with CR=0.048<0.1, which met the methodological requirements [35].

The weight calculation of the indicator layer followed the same logical path. Judgment matrices for emergency braking assistance, voice correction, fatigue monitoring, haptic warning, and one-key operation/shortcut entrance under the B1 criterion were constructed respectively, as well as judgment matrices for ARHUD, voice assistant, adjustable font size, and icons mainly based on physical images under the B2 criterion. The local weights WCi/Bj of each indicator under the respective criteria were solved using the sum-product method [36].

4.5.3. Consistency test

AHP requires the judgment matrix to have reasonable consistency to ensure the logical consistency of experts' subjective judgments. The rationality of weight allocation directly depends on whether the judgment matrix meets this requirement [37]. Therefore, after obtaining the weight vectors of indicators at all levels, a strict consistency test process must be carried out [38].

The core of the test is to calculate the maximum eigenvalue (λmax) of the judgment matrix. For the judgment matrix constructed in this study, the calculation process of its maximum eigenvalue is as follows [39]:

$$\lambda_{max} = \sum_{i=1}^{n} \frac{(AW)_i}{nW_i}$$

Where A is the judgment matrix, W is the eigenvector, n is the order of the matrix, and (AW)i represents the i-th element of the vector AW. Substitute the specific values of the relevant levels in this study:

$$\lambda_{max} = \frac{(AW)_1}{nW_1} + \frac{(AW)_2}{nW_2} = \frac{1.719}{2 \times 0.857} + \frac{0.286}{2 \times 0.143} = 1.998$$

Based on the calculated maximum eigenvalue, the consistency index (CI) is further calculated to measure the degree of deviation of the judgment matrix from consistency. Substitute the calculated value [40]:

$$CI = \frac{1.998 - 2}{2 - 1} = \frac{-0.002}{1} = -0.002$$

Since the consistency index should theoretically be greater than or equal to 0, and the calculated value is extremely small (0.002), it can be regarded as a small floating error in the calculation process, so the actual value taken in the subsequent calculation is CI=0.

To more objectively evaluate the consistency level, it is necessary to compare CI with the average random consistency index (RI) of random judgment matrices of the same order and calculate the consistency ratio (CR). According to the standard RI value table given by Saaty, when the matrix order n=2, the corresponding RI=0, so CR=0 is calculated. For the case of n=2, theoretically, as long as the judgment matrix satisfies reciprocity, its consistency is naturally satisfied, so it can be directly determined that the judgment matrix of this layer passes the consistency test [41].

4.5.4. Weight distribution and design implications

The weight calculation results are shown in Table 3.3, which reveals the core law of age-friendly design: the weight ratio of B1 to B2 in the criterion layer reaches 6:1, quantitatively verifying the absolute priority of safety demands in the elderly driving scenario [42]. This distribution feature indicates that under the constraint of limited design resources, interface optimization should give priority to ensuring the realization of safety functions.

Table 3. Overview of demand weight calculation results

Demand Indicator	Criterion Affiliation	Criterion Weight	Local Weight	Global Weight	Priority
Emergency braking assistance (C1)	B1	0.857	0.352	0.302	1
Voice correction (C2)	B1	0.857	0.281	0.241	2
Fatigue monitoring (C3)	B1	0.857	0.201	0.172	3
Haptic warning (C4)	B1	0.857	0.166	0.142	4
One-key operation/shortcut entrance (C5)	B1	0.857	0.100	0.086	5
ARHUD (C6)	B2	0.143	0.417	0.060	6
Voice assistant (C7)	B2	0.143	0.283	0.040	7
Adjustable font size (C8)	B2	0.143	0.185	0.026	8
Icons mainly based on physical images (C9)	B2	0.143	0.115	0.016	9

In the global weight ranking of the indicator layer, safety functions occupy the top five positions: emergency braking assistance, voice correction, fatigue monitoring, haptic warning, and one-key operation/shortcut entrance. It is worth noting that the global weight of C1 exceeds the sum of the weights of all functions under the B2 criterion, highlighting the pillar position of the active safety system in age-friendly design [43]. In terms of Attractive Qualities, although ARHUD has the highest weight within the B2 criterion, its global impact is only ranked sixth due to the dilution of the criterion layer weight, and the weights of other functions decrease in a stepped manner. This distribution structure provides clear guidance for design practice: the development of safety functions should follow the progressive order of C1→C2→C3→C4→C5, while experience optimization functions should be implemented selectively on the premise of ensuring the safety baseline [44].

Through the AHP model, this study established a quantitative decision-making basis for demand priority. Its output results not only verified the age-friendly design principle of "safety first" but also accurately identified the key levels within the safety function system. The weight distribution indicates that emergency braking assistance and voice correction functions should be the primary focus of interface optimization, while fatigue monitoring and haptic warning systems form the second echelon of safety design. This conclusion provides measurable design constraints for subsequent prototype development, ensuring that limited R&D resources are accurately invested in the functional modules that contribute the most to the driving safety of the elderly.

The calculation results reveal key design insights: in the criterion layer, the Must-be Qualities with a weight of 0.857 are significantly higher than the Attractive Qualities with 0.143, quantitatively confirming the core position of safety functions in age-friendly design [45]. The global weight ranking of the indicator layer further shows that safety demands occupy the top five positions—emergency braking assistance, voice correction, fatigue monitoring, haptic warning, and one-key operation/shortcut entrance. Among them, the weight of the top function even exceeds the sum of the weights of all Attractive Qualities. This distribution law provides clear guidance for design practice: interface optimization should give priority to ensuring the realization of the active safety system, especially focusing on the development of emergency braking assistance and voice correction functions; while experience optimization functions such as ARHUD have a high weight within the Attractive Qualities, their global influence is only ranked sixth due to the restriction of the criterion layer weight, and should be implemented in phases after the safety baseline is improved [46]. This weight system converts user demands into measurable design constraints through mathematical modeling, establishing a scientific decision-making basis for subsequent prototype development.

5. Design strategies, research summary and outlook

5.1. Age-friendly design strategies based on weight analysis

Integrating the Kano model demand classification results and AHP weight ranking, this study identified the core demands of the elderly driving group in using in-vehicle HMI. The results show that safety factors are in the primary position, followed by operational simplicity and visual clarity. Multimodal support and emotional care have supplementary value in improving interaction experience. Based on this, this study proposes the following age-friendly design strategies:

1. Safety-First Functional Guarantee

Take functions such as emergency braking assistance, voice correction, and fatigue monitoring as the core elements of HMI design to ensure the bottom line of driving safety.

Introduce redundant prompt mechanisms of vision, hearing, and touch in the interaction mode to ensure the accuracy and timeliness of key information transmission.

Set up a secondary confirmation mechanism for high-sensitivity operations that may cause risks to improve the fault tolerance of the system.

2. Concise and Efficient Operation Paths

Optimize the functional hierarchy structure, reduce redundant steps, and provide one-key access to key function entrances (such as navigation and emergency calls).

Retain core physical control components to avoid complete reliance on touch operations for interaction, thereby reducing the operational burden on elderly users.

Ensure consistent and intuitive interaction logic to avoid increasing learning costs due to excessive innovation.

3. Clarity of Visual Presentation

The interface should support adjustable font size, adopt high-contrast color schemes, and use icons with clear semantics to adapt to information recognition obstacles caused by decreased eyesight.

The information hierarchy needs to be concise and clear, avoiding presenting excessive information at one time to reduce cognitive load.

4. Multimodal Support and Emotional Care

Improve the recognition rate and adaptability of voice interaction, allowing personalized adjustment of speech rate and volume to reduce the interference of environmental noise.

Add haptic feedback to key prompts to build multimodal redundant channels and enhance the safety and reliability of interaction.

Introduce auxiliary functions with care attributes, such as health monitoring, fatigue reminders, and humanized voice styles, to improve users' psychological sense of security and willingness to use.

5.2. Research conclusions

Taking the elderly driving group as the research object, this study combines the Kano model and AHP method to construct a systematic research framework covering demand identification, attribute classification, and priority ranking. The research conclusions show that:

The primary concerns of elderly drivers in in-vehicle HMI focus on safety guarantee and operation simplification, among which functions such as emergency braking assistance and voice correction are significantly leading in weight ranking;

Visual presentation and multimodal support are effective ways to reduce information processing burden and improve interaction experience;

Emotional and caring design, although not the primary demand, plays a positive role in improving system acceptance and continuous use.

This study not only verifies the age-friendly design principle of "safety first" but also provides quantitative basis and practical paths for the optimization of in-vehicle HMI.

5.3. Research innovations and limitations

Innovations:

Methodologically, this study is the first to systematically apply the combined Kano model and AHP method in the age-friendly research of in-vehicle HMI, forming a comprehensive framework with both qualitative and quantitative analysis advantages;

In terms of results, based on empirical data, the study identifies the core demand priorities of the elderly driving group and proposes targeted design strategies accordingly.

Limitations:

The number and coverage of research samples are limited, and the universality of the results needs further verification;

This study only stays at the level of strategy proposal and has not carried out the implementation and usability testing of high-fidelity prototypes.

5.4. Future outlook

In view of the above limitations, future research can be deepened in the following directions:

High-fidelity prototype verification: Develop a prototype interface based on the conclusions of this study, and verify its usability and effectiveness through experimental design;

Multi-scenario adaptation research: Investigate the differences in age-friendly HMI demands under different driving environments (such as nighttime driving, high-speed driving, and severe weather);

Cross-cultural and cross-vehicle type expansion: Compare the demand differences of the elderly driving group under different cultural backgrounds and different vehicle types (such as new energy vehicles and traditional fuel vehicles);

Integration of intelligence and personalization: Introduce artificial intelligence learning and personalized adaptation mechanisms to enable the system to actively adjust interaction methods to further reduce the use threshold for elderly drivers.

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