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Evaluation of Adjustment Effects of Highway Guide Signs Based on the TOPSIS Method

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Abstract: With the rapid expansion of highway networks, the demand for timely and reliable road information has steadily increased. However, some guide signs on newly built or extended highways in China have not been updated or adjusted in time, resulting in incomplete information and non-standard setups. These issues not only affect drivers' navigation experience but may also negatively impact road safety and traffic efficiency. Therefore, it is crucial to establish a scientifically sound evaluation system and a comprehensive assessment model for highway guide signs. This study selected a representative highway (G2 Expressway in China) as the research subject and combined questionnaire surveys with field investigations to identify common issues such as vague information and irregular placement of guide signs. Through an in-depth analysis of travel demand, the core requirements of drivers were summarized as safety, efficiency, and comfort. Based on these insights, the study proposes four key design principles for guide signs: standardization, readability, continuity, and consistency. A set of quantifiable evaluation indicators was developed through a comprehensive analysis of key factors affecting signage performance, and factor analysis was applied to verify the independence and rationality of the indicators. On this basis, an evaluation model was constructed using the technique for order preference by similarity to ideal solution (TOPSIS) to scientifically quantify the effectiveness of guide signs. The model was applied in a field study on the Hebei section of the G2 Expressway in China (with comprehensive traffic sign coverage, high traffic volume, and more traffic sign issues), with results demonstrating the feasibility and practicality of the proposed evaluation system and model. This research offers a systematic solution to enhance the service quality of highway guide signs and provides essential references for future highway planning and management practices. It aims to comprehensively improve drivers' travel experiences and promote the development of sustainable and intelligent transportation networks, offering valuable insights for building integrated urban systems.

Keywords: sustainable transportation; traffic safety; guide sign performance; TOPSIS evaluation; field investigation; driver experience

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1. Introduction

With the rapid development of the economy, the demand for road transportation has surged, accompanied by swift road network expansion. China's highway network,

for instance, has grown from 85,000 km in 2011 to 183,600 km in 2023, forming a large-scale and increasingly complex network. This expanding infrastructure has provided a solid foundation for diverse travel modes [1]. As the primary medium for conveying critical road information, highway guide signs are essential in minimizing driver errors and reducing risks. However, statistics reveal that accidents involving traffic signs and markings constitute 60% of all traffic accidents, underscoring how inadequate or inaccurate signage can substantially elevate driving hazards [2]. For instance, missing or unclear signs may lead drivers to miss exits or fail to anticipate sharp curves. Therefore, optimizing the design and placement of highway guide signs is an important issue in current road traffic management [3,4]. With the further expansion of the highway network, the opening of new or extended highways has altered driving routes, requiring timely adjustments to guide signs along the routes to ensure the continuity of network information. In densely connected highway networks, guide signs not only need to direct drivers to single destinations but also provide multi-level information to prevent missed exits or incorrect turns. These demands place higher requirements on the design and setup of signage [5,6]. Therefore, it is essential to establish a scientific evaluation method and indicator system to comprehensively analyze the effectiveness of these adjustments.

Existing research on the evaluation of traffic signs primarily focuses on the impact of design elements, information load thresholds, and driver characteristics on the effectiveness of traffic sign usage, as well as the methods used to assess traffic sign systems. Studies on design elements often emphasize how features such as color, font size, shape, and contrast influence the visibility and comprehension speed of drivers [7–9]. Researchers assess the effectiveness of these elements under various conditions, including low light, poor weather, and complex road environments [10,11]. Liu et al. [12], applying human ergonomics principles, developed an evaluation model encompassing information needs, comprehension, and information load. In terms of setting information thresholds, studies show that excessive information can increase drivers' visual load, potentially leading to adverse driving behaviors and even causing traffic accidents [13–16]. Lv et al. [17] demonstrated through experiments that traffic signs with varying amounts of information significantly affect driving load. Chang et al. [18] observed a significant reduction in legible reading distance as the information load on variable message signs increased. Notably, when the number of messages reached six, drivers' comprehension accuracy declined sharply. Ren et al. [19] studied the effectiveness of bilingual guide signs (in Chinese and English) for drivers with different language backgrounds on Chinese highways. Yang et al. [20] noted that cantilever signs can accommodate up to five pieces of information, while gantry signs can hold up to nine.

Different characteristics, such as age and education, also influence the visibility and comprehension of traffic signs [21–24]. Taheri et al. [25] investigated the effect of personal characteristics and traffic sign design on traffic sign usability and found that four of the five personal characteristics studied (e.g., age, education level, and driving experience) correlated significantly with traffic sign usability. Taamneh et al. [26] examined the relationship between drivers' personal characteristics and their familiarity with and comprehension of traffic signs. In research on the effectiveness evaluation of traffic signs, scholars have approached the topic from multiple perspectives, employing a variety of methods for analysis and assessment [27–29]. Wang [30] developed an evaluation system for traffic safety facilities by examining their impact on drivers and vehicles, incorporating indicators such as speed and driving trajectories into the framework. Yao et al. [31] developed the guide sign evaluation method to assess the effectiveness of traffic signs through simulation experiments and applied it to the evaluation of traffic signs at intersections. Li et al. [32] evaluated and classified interchange diagrammatic guide sign complexity, proposing a

theoretical framework for quantitative assessment that offers valuable insights for traffic sign design and application.

In summary, existing research has made significant progress in areas such as the layout design of traffic signs, information load control, driver characteristics, and evaluation methods. Studies have shown that design elements (e.g., color, font size, contrast, and layout) significantly impact drivers' visibility and comprehension speed, while reasonable control of information load helps prevent information overload and reduces drivers' cognitive burden. Moreover, research indicates that drivers' personal characteristics (e.g., age, experience, and educational background) strongly affect their ability to recognize and understand sign information, suggesting that sign design should accommodate the needs of diverse groups. However, with the continuous expansion of the highway network and increasing complexity of road structures, traditional sign design and evaluation methods face new challenges: (1) Delayed information updates: New or expanded highways often alter travel routes, but signage on certain sections may not be updated promptly, leading to misjudgments by drivers. (2) Increasingly complex information hierarchies: In dense road networks, signs must provide multi-level route guidance to ensure drivers can accurately select directions at complex interchanges. (3) Lack of standardization and consistency: Inconsistencies in information delivery, layout specifications, and continuity among regional signage systems undermine the navigation experience for drivers. (4) Insufficient comprehensive evaluation systems: Existing studies tend to focus on individual design elements or specific case analyses, lacking systematic evaluation models for complex networks.

Given these challenges, this study proposes a comprehensive evaluation framework synthesizing insights from driver behavioral analytics, cognitive science principles, and traffic engineering methodologies. By integrating subjective and objective assessment methods, it contributes to the academic discourse on optimizing traffic signage systems for safety, efficiency, and user experience in complex highway networks.

2. Method

2.1. Evaluation Indicator Selection

The purpose of evaluating the effectiveness of guide signs is to optimize their design and usage, enhancing their guidance capability. Well-designed signs can effectively direct and influence driver behavior, providing a safer and more comfortable traffic environment for highway users. Therefore, conducting a comprehensive evaluation of guide signs is of significant practical importance. The selection of evaluation indicators should follow these principles: (1) Comprehensive reflection: The indicators should fully capture the major impacts across the entire road network. (2) Strong independence: Indicators should be as independent as possible to avoid excessive intercorrelation. (3) Moderate quantity: The number of indicators should remain reasonable, avoiding redundancy, with a preference for quantitative indicators. (4) Practicality and feasibility: The indicators should be operationally feasible to ensure the practicality and effectiveness of the evaluation.

Factor analysis is an effective tool for simplifying and reducing the dimensionality of indicator datasets, particularly when numerous indicators overlap or exhibit complex relationships [33]. This approach helps streamline the model structure, ensuring it remains concise and scientifically robust. The general model for factor analysis can be expressed as [33] follows:

$$X_i = \alpha_{i1}F_1 + \alpha_{i2}F_1 + \ldots + \alpha_{ib}F_b + \varepsilon_i \; i = 1, 2, \ldots, n \quad (1)$$

where X_i represents the i-th evaluation indicator, with a total of n indicators; α_{ib} is the weight of the b-th common factor on the i-th evaluation indicator; F_b represents the m-th common factor in the evaluation indicator system; and ε_i is the error term for the i-th

evaluation indicator, representing the portion of information not captured by the common factors [34].

In factor analysis, the Kaiser–Meyer–Olkin (KMO) test quantifies the inter-correlation strength of preliminarily selected indicators, and Bartlett's sphericity test assesses compliance with factor analysis assumptions [34]. Following indicator filtration through these diagnostic tests, the factor score matrix is utilized to examine inter-indicator correlations. This methodology facilitates both the systematic optimization and evidence-based construction of highway guide sign evaluation frameworks, thereby establishing a quantifiable foundation for scientifically rigorous assessments of signage efficacy.

2.2. Indicator System Construction

The construction of an evaluation indicator system should follow a value-driven, goal-oriented logical approach. This study adopts a three-stage "Value-Goal-Indicator" evaluation concept to develop the evaluation system for assessing the effectiveness of highway guide signs.

Figure 1 illustrates the detailed construction process, showing the systematic flow from field surveys to demand analysis and indicator selection. The field survey involves collecting data through questionnaires and on-site observations to systematically investigate the current status of highway guide signs. During this stage, drivers' demands for signage are gathered, serving as the foundational data for demand analysis. The collected data are then summarized and analyzed to interpret drivers' subjective evaluations through reliability and validity assessments. This process aims to capture drivers' specific traffic-related needs. Based on these findings, key factors influencing drivers' requirements are identified through quantitative analysis. Relevant standards and guidelines are referenced to propose indicators that reflect the effectiveness of guide signs. If the initial selection includes too many indicators with overlapping or highly correlated attributes, simplification is performed. This step retains only a few comprehensive indicators that capture most of the information, ensuring the simplicity and effectiveness of the system. Ultimately, the evaluation indicator system is developed based on the drivers' needs analysis and corresponding indicators, providing a scientific approach to assess the actual performance of highway guide signs.

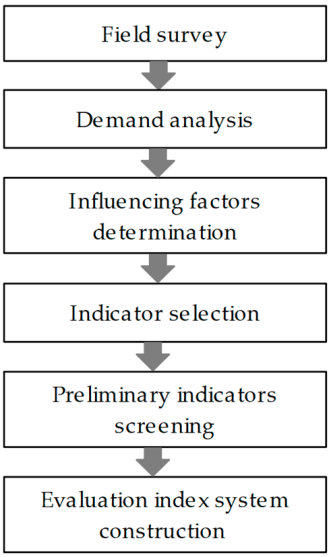


Figure 1. Indicator System Construction Process.

2.3. Indicator Weight Determination

The importance of each evaluation indicator varies, making it essential to assign appropriate weights to them. Calculating weights is a critical part of comprehensive evaluation, and different methods correspond to different underlying principles. When selecting a suitable method, it is important to consider the characteristics of the data. Common weight calculation methods can be categorized into four types based on their calculation principles.

(a) Factor analysis and principal component method [33]: This method utilizes the principle of data information concentration and calculates weights based on variance explanation rates. (b) Entropy method (EM) [34]: This method calculates weights based on the entropy value of data, which reflects the amount of information. (c) Analytic hierarchy process (AHP) and priority diagram method [35]: These are subjective assignment methods that typically involve scoring by experts or through questionnaire surveys to obtain scores indicating the importance of each indicator. The higher the score, the greater the weight of the indicator. (d) CRITIC, independence weight, and information quantity weight [36]: These methods calculate weights based on the volatility of data or the correlation between different data points. For multi-objective comprehensive evaluation, the AHP and EM are commonly used.

2.3.1. Determining Weight Using the AHP

(1) Constructing the judgment matrix

Experts conduct pairwise comparisons of the n indicators within the same level, assessing their relative importance. A proportional scale of 1 to 9 is used for this evaluation, with the specific scoring criteria shown in Table 1 [35].

Table 1. Definition of judgment matrix scale.

Scale	Meaning
1	Two elements are equally important.
3	The former is slightly more important than the latter.
5	The former is significantly more important than the latter.
7	The former is strongly more important than the latter.
9	The former is extremely more important than the latter.
2, 4, 6, 8	Intermediate values between the above adjacent judgments.
Reciprocal	The importance scale of the latter compared to the former.

Construct the judgment matrix A (orthogonal matrix); a_{ij} represents the comparison results of the i-th factor relative to the j-th factor [35]:

$$A = (a_{ij})_{n\times n} = \begin{pmatrix} a_{11} & a_{12} & \dots & a_{1n} \\ a_{21} & a_{21} & \dots & a_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ a_{n1} & a_{n2} & \dots & a_{nn} \end{pmatrix} \quad (2)$$

(2) Calculating weights

Perform geometric averaging (root method) on each row vector of matrix A, then normalize it to obtain the weights of each evaluation indicator and the characteristic vector W:

$$w_i = \frac{\overline{w_i}}{\sum_{i=1}^{n} \overline{w_i}}, \; w = \begin{Bmatrix} w_1 \\ w_2 \\ \vdots \\ w_n \end{Bmatrix} \tag{3}$$

(3) Consistency check

Calculate the maximum eigenvalue λ_{max}:

$$\lambda_{max} = \frac{1}{n}\sum_{i=1}^{n} \frac{(AW)_i}{w_i}. \tag{4}$$

Calculate consistency index (CI), random consistency index (RI), and consistency ratio (CR):

$$CI = (\lambda_{max} - n)/(n-1) \tag{5}$$

The RI is related to the order of the judgment matrix. Generally, the higher the order of the matrix, the greater the likelihood of random consistency deviation. The specific corresponding relationship is shown in Table 2.

Table 2. Average random consistency index (RI).

n	1	2	3	4	5	6	7	8	9	10	11	12
RI	0	0	0.52	0.89	1.12	1.26	1.36	1.41	1.46	1.49	1.52	1.54

To check the consistency of the judgment matrix, it is necessary to compare the CI with the RI. The formula for the CR is as follows:

$$CR = CI/RI \tag{6}$$

Typically, if CR < 0.1, the judgment matrix is considered to have passed the consistency test; otherwise, the matrix does not exhibit satisfactory consistency.

2.3.2. Determining Weight Using the EM [34]

(1) Calculate the proportion of the *i*-th sample under the *j*-th indicator:

$$P_{ij} = \frac{X'_{ij}}{\sum_{i=1}^{n} X'_{ij}} \tag{7}$$

(2) Calculate the entropy value of the *j*-th indicator:

$$E_j = -k\sum_{i=1}^{n} P_{ij} ln(P_{ij}) \tag{8}$$

where k is a normalization constant, $k = 1/ln(n)$, and when $P_{ij} = 0$, assume $P_{ij} ln(P_{ij}) = 0$.

(3) Calculate the redundancy of information entropy:

$$D_j = 1 - E_j \tag{9}$$

(4) Calculate the weights of each indicator:

$$W_j = \frac{D_j}{\sum_{j=1}^{m} D_j} \tag{10}$$

2.4. Comprehensive Evaluation Using the TOPSIS Method

2.4.1. Comparison of Common Evaluation Methods

Different highway users have varying needs for highway guide signs, influenced by multiple factors, making the choice of evaluation method crucial. Common comprehensive evaluation methods are shown in Table 3 [37]. Each method is suitable for different scenarios. TOPSIS can be combined with the entropy and AHP methods to determine weights and conduct comprehensive ranking. For multi-indicator comprehensive evaluation of guide sign effectiveness, TOPSIS is the most appropriate method. Its core principle lies in examining the proximity of indicator values to the ideal solution, making it highly effective for this type of analysis.

Table 3. Summary of common evaluation methods.

Method	Description
FA	Condenses multiple quantitative indicators into composite indicators.
AHP	Constructs a judgment matrix through pairwise indicator comparison to calculate weights.
FCE	Uses fuzzy mathematics to evaluate indicators that are difficult to quantify.
EM	Analyzes the amount of information and variability each indicator provides to compute weights.
GRA	Measures the degree of correlation between standard values and assessed items.
TOPSIS	Ranks alternatives by calculating the distance from the ideal and negative ideal solutions.
DEA	Determines optimal weights based on real data to calculate the relative efficiency of decision units.

2.4.2. TOPSIS Method Overview and Steps

TOPSIS is a widely used multi-criteria decision analysis method that ranks alternatives based on their proximity to the ideal solution [38]. The two core concepts in TOPSIS are the "ideal solution" and the "negative ideal solution": The ideal solution is a hypothetical option where all attribute values are optimal. The negative ideal solution is a hypothetical option where all attribute values are the least favorable. The ranking of alternatives is determined by comparing their distances from the ideal and negative ideal solutions. An alternative that is closest to the ideal solution and furthest from the negative ideal solution is considered the best option. TOPSIS is commonly applied in fields such as transportation planning and product selection, where a clear ranking of alternatives is needed. In this study, we adopted TOPSIS due to its ability to clearly rank alternatives by positioning them relative to both the ideal and negative ideal solutions. This approach is particularly beneficial when evaluating expressway routes consisting of multiple links, as it allows for an intuitive and transparent comparison. While other evaluation methods provide comprehensive rankings, TOPSIS emphasizes the distinction between the best and worst alternatives, which is critical for decision-making in complex transportation planning.

The fundamental principle of the TOPSIS method lies in evaluating alternatives by their proximity to the optimal and least favorable solutions. The following are the seven steps involved in implementing TOPSIS for system evaluation or decision-making: (a) Construct a decision matrix: Gather performance data for each alternative based on multiple indicators, ensuring all key metrics are captured. (b) Normalize the indicators: Normalize the decision matrix to eliminate the influence of different measurement units. (c) Determine indicator weights: Assign weights to the indicators based on the evaluation goals and expert knowledge. (d) Construct a weighted decision matrix: Multiply the normalized matrix by the weights to form the weighted decision matrix. (e) Identify the optimal and least favorable solutions: Determine the ideal and negative ideal solutions based on the best and worst values for each indicator. (f) Calculate the distance to the optimal and least

favorable solutions: Measure the distance of each alternative from the ideal and negative ideal solutions. (g) Calculate the closeness coefficient: Evaluate the degree to which each alternative approaches the ideal solution and rank it accordingly.

3. Survey Plan

Guide signs should be designed in accordance with highway and traffic conditions, providing users with information (i.e., destinations, distances, key public facilities, driving directions, etc.) to ensure smooth arrival at their destinations [39]. However, as the highway network becomes increasingly dense, the guide information has grown more complex, leading to issues such as discontinuity, inconsistency, and non-compliance with standards in some signs. Therefore, it is essential to conduct field investigations to identify the main problems with highway guide signs.

3.1. Survey Design

The goal of this survey is to gather subjective evaluations from highway users about highway guide signs and understand their needs. Additionally, the survey aims to explore specific issues with guide signs from the perspective of regulatory compliance and scientific design, analyzing the needs of travelers regarding these signs. To ensure comprehensive data collection, the selected survey section must include at least five interchanges to capture various potential problems with guide signs. The survey consists of two steps: (a) Questionnaire survey: Gather drivers' feedback on their experience with guide signs and any identified problems. (b) Field investigation: Based on issues highlighted in the questionnaires, extensive data collection is performed to analyze the guide signs. The goal is to summarize the major problems in the setup of guide signs across China's highway network.

3.2. Survey Implementation

The survey focuses on the representative section of the Beijing–Shanghai Expressway (G2), covering the Beijing, Tianjin, and Hebei segments. This highway stretches across six provinces and municipalities, including Beijing, Tianjin, Hebei, Shandong, Jiangsu, and Shanghai, with a total length of 1219 km. Through preliminary research, it is known that there are a large number of traffic signs on this highway, and there are different types of problems. As it passes through a dense and complex highway network with diverse information needs, this section offers valuable insights into the challenges faced in highway guide sign systems. The intersections where guide sign data are collected are summarized in Table 4.

Table 4. Crossroads for guide sign data collection.

No.	Administrative Level	Road Number	No.	Administrative Level	Road Number
1	National Expressway	G3	7	Provincial Expressway	S60
2	Provincial Expressway	S40	8	National Highway	G104
3	National Expressway	G2501	9	Provincial Expressway	S6
4	National Expressway	G18	10	National Highway	G307
5	Provincial Expressway	S7	11	Provincial Expressway	G1811
6	Provincial Expressway	S50			

3.2.1. Questionnaire Survey

The questionnaire survey was conducted at highway service areas, targeting four categories of respondents: taxi drivers, private car drivers, bus drivers, and truck drivers,

to account for their differing driving preferences. Private car drivers were the focus of this research, as they tend to prioritize convenience and comfort in their travels.

The content of the questionnaire was designed based on an extensive review of relevant literature and consultation with experts in traffic safety and frequent drivers. A draft version of the questionnaire was then subjected to the pilot study phase, which included 25 items. This phase aimed to identify issues such as unclear wording, unreasonable options, and incomplete coverage. Feedback from respondents and expert reviews during this phase guided item modifications and reductions to enhance clarity and relevance. For reliability and validity testing, we employed Cronbach's alpha as the primary measure of internal consistency, with a threshold value of 0.7, which is commonly accepted as indicating adequate reliability.

The survey was divided into two phases: (1) Pilot survey: This was conducted on a small scale to identify issues such as unclear wording, unreasonable options, and incomplete coverage in the questionnaire. Adjustments were made based on the feedback received. (2) Formal survey: After finalizing the questionnaire content, the formal survey was conducted. Upon collecting the responses, the reliability and validity of the questionnaires were analyzed, leading to the removal of any invalid surveys that contained all identical answers or omitted key questions. While some questionnaires were incomplete, this did not significantly impact the overall reliability and validity, thus they were retained.

3.2.2. On-Site Survey

This survey focused on the design and placement of direction signs, particularly concerning the information needs of drivers seeking their destinations, as well as the selection of sign information and the continuity of directional signs. By combining real-time vehicle photography with GPS positioning, the team collected photos of traffic signs and matched them with road network maps, conducting objective evaluations based on national standards and industry norms to identify major issues in the existing direction sign setups.

The survey team consisted of three members: one driver, one person responsible for photographing signs and collecting data, and one recorder. The survey commenced from a designated starting point, with both the sign imaging collection equipment and GPS positioning devices activated simultaneously as the vehicle traveled along the main highway at normal speeds. Direction signs were thoroughly photographed at the interchanges between highways, and the vehicle turned back at the next exit to gather information from the opposite direction. When the survey vehicle reached the intersection of the highway and a national road, it entered the national road and captured sign information for 2 km in both directions. After reaching the boundary between Hebei and Shandong provinces, the vehicle turned around at the nearest exit and returned along the same route to collect reverse direction sign information.

3.2.3. Data Processing

The data collected from the questionnaires and on-site surveys were processed. A total of 236 valid samples were recovered from the questionnaire survey, of which 203 (86%) were male and 33 (14%) were female. Private vehicle drivers and commercial vehicle drivers accounted for 61% and 39%, respectively. The survey collected relevant data on direction signs along the G2 expressway in the Beijing-Tianjin-Hebei region and connecting roads, totaling 558 signs. After data processing and analysis, it was found that 99 direction signs did not meet relevant standard requirements, accounting for 17.7% of the total. The proportional statistics of various issues are shown in Table 5.

Table 5. Statistics of issues in highway direction sign settings.

Main Issues	Quantity
Sign information and text height do not meet requirements	48
Sign layout design does not comply with national standards	44
Improper sign placement	4
Inconsistent sign information	10
Information overload on the sign layout	8

3.3. Analysis of Questionnaire Data

Topic 1: Importance of guide signs

In the survey, team members asked respondents: "Which guidance tools do you rely on while driving? (Please rank them in order of importance)". Drivers ranked the options based on their experience, and the sequence was assigned values of 1, 2, 3, and 4, with lower values indicating higher priority. The average value for each option was then calculated to assess its overall importance. The lower the average value, the more important the option was perceived to be. The statistical results are shown in Table A1 (N represents the number of respondents who selected each item). Vehicle navigation systems emerged as the most critical tool, followed by guide signs, maps, and asking locals. Notably, while vehicle navigation is frequently relied upon, 78% of drivers stated they trust road signs more when discrepancies arise, indicating that standardized road signs remain a trusted source of information. This suggests a need for enhanced precision in navigation systems to complement the consistency of road signs.

Topic 2: Overall evaluation and main issues of guide signs

In this survey, a statistical analysis of the question, "Have you ever taken a wrong turn due to guide signs?" revealed that approximately one-third of respondents admitted taking wrong turns due to guide signs, indicating a need for improvement in their accuracy and reliability. Additionally, a statistical analysis of the question, "What do you think are the main problems with highway guide signs?", as shown in Table A2 (see Appendix A), highlighted the main issues identified by the respondents. The main issues identified, ranked by importance, included missing useful information, poor visibility, complicated graphics, information overload, inconvenient placement, and signs being blocked by trees. These problems highlight challenges such as difficulty in finding essential details, insufficient visibility, and complex designs that hinder quick interpretation, particularly under time constraints. Addressing these issues through clearer, more visible, and user-friendly signage is essential to enhance safety and driving efficiency.

Topic 3: Driver-focused guidance information

To conduct an in-depth study on the issue of "unable to find useful information" reported by drivers, we further inquired about which information drivers primarily focus on in highway signs. The statistical analysis results for the survey question "Which information do you mainly use from highway signs (multiple choice)?" are presented in Table A3 (see Appendix A).

The survey revealed that the most critical guidance information for drivers includes "names of reachable destinations" (75.0%), "names of reachable highways" (62.3%), and "current highway name" (27.1%). For unfamiliar destinations, drivers prioritize information about "highways along the route", followed by "traffic hubs and interchanges" and "towns along the route". While drivers are generally satisfied with highway signs, issues such as the inability to find useful information, unclear signage, and complex graphics remain. These findings emphasize the importance of clear, accessible, and relevant information on

guide signs to enhance navigation and reduce errors. Further field research is planned to address these concerns.

3.4. Issues Identified in Highway Guide Signs

3.4.1. Configuration or Placement Problems

A review of guide signs along the G2 Expressway in the Beijing-Hebei section identified several configuration and placement issues, especially with distance and exit direction signs.

(1) Improper placement of distance signs

According to the standards, distance signs should be placed 1 km before the end of the acceleration lane in an interchange and must be repeated at least every 5 km [39]. However, the investigation identified the following issues: (a) Insufficient distance between signs: Some signs are only spaced 1 km apart, failing to meet the 5 km requirement. (b) Incorrect placement: Some signs are installed near ramp exits, which can distract drivers entering the mainline, posing safety risks.

(2) Incomplete configuration of exit direction signs

Standards stipulate that exit direction signs should be placed at intervals of 2 km, 1 km, 500 m, and at the exit point along the deceleration lane of expressways or urban roads [39]. However, the following problems were noted: (a) Missing levels: Many locations lack the 500 m level signs. (b) Insufficient pre-warning: Some places only provide 500 m signs and action point markers, but omit the 2 km and 1 km signs, posing safety hazards.

(3) Incomplete entrance direction signs

The standards recommend placing entrance direction signs on roads connecting to expressways, at 2 km, 1 km, 500 m, and at the reference point [39]. However, in certain cases, signs are missing, particularly at the 500 m mark, where only those of other places are present.

(4) Incomplete service area signs

Service area signs are required at 2 km, 1 km, 500 m, and at the start of the deceleration lane [39]. However, some service areas lack 2 km signs, leading to insufficient information for drivers.

3.4.2. Layout Design Problems

An analysis of collected guide signs reveals that the layout design of some signs fails to comply with standard regulations. The following two key issues were identified.

(1) Information overload on signs

According to the standards, no more than six destinations should be displayed on a single guide sign, and the total number of destination names on signs within the same gantry structure should not exceed eight [39]. However, the survey found some cases of excessive information, with up to nine destinations shown on a single gantry. This overload can make it difficult for drivers to quickly extract relevant information, potentially compromising road safety.

(2) Improper sequence of information on distance signs

The standards recommend that distance signs display up to three rows of information, arranged in descending order of proximity (i.e., from nearest to farthest, top to bottom) [36]. However, the survey found that some signs contained four rows of information, with the sequence sometimes reverse-listed from farthest to nearest. This inconsistency introduces

unnecessary complexity, making it harder for drivers to quickly interpret the information, which could lead to delayed decision-making and increased driving risks.

3.4.3. Information Selection Problems

The analysis of the collected highway guide signs revealed the following key issues regarding the selection of sign information.

(1) Inconsistent guide information

According to standards, the information displayed on exit signs, including advance exit signs, exit markers, and signs at branch points after the exit, must remain consistent throughout. Additionally, the first row of the distance sign should align with the destination shown on the subsequent exit marker [39]. However, the survey found that some exit signs presented conflicting information, and the distance signs lacked correspondence with upcoming exit markers. Furthermore, the guide information on exit markers was inconsistent with that on signs at post-exit branch points, leading to driver confusion.

(2) Lack of hierarchical information selection

Standards require that distance signs follow a hierarchical structure: the first row should display the destination accessible via the next interchange, while the second and third rows should indicate destinations at increasing distances (Tier B and Tier A information, respectively) [39]. However, the survey identified non-compliance, where signs failed to use this hierarchical format and omitted highway numbers, resulting in inconsistencies with previous signs and creating information overload.

(3) Inconsistent reference points for distance calculations

The standards specify that distance calculations must use a consistent reference point, such as the beginning of the taper at deceleration lanes when guiding towards exits [39]. However, discrepancies were found in the network, with multiple distance signs using inconsistent reference points. This inconsistency can mislead drivers regarding the actual distance to destinations, reducing the accuracy of navigation systems and compromising driving safety.

3.5. Summary of Survey Questions

Based on in-depth analysis of the driver survey and field research on highway guide signs, the main issues identified and their proportions are as follows: (a) Non-compliance of sign information and font height: 42%; (b) Non-standard sign layout design: 39%; (c) Improper sign placement: 3%; (d) Inconsistent guide information: 9%; (e) Overloaded sign content: 7%. These issues can be grouped into three main categories: (a) Sign layout design: The signs must adhere to relevant design standards to ensure readability and usability. (b) Sign placement and configuration: Proper placement of signs is essential for maximizing visibility and ensuring safe driving behavior. (c) Selection of guide information: The information on signs must be accurate, consistent, and easy to understand to prevent driver confusion. The findings indicate that highway guide signs need improvements in layout design, accurate information selection, and rational placement to ensure they meet safety standards and facilitate efficient navigation.

4. Construction of Evaluation Index System

The primary function of guide signs is to guide drivers by providing information about routes to destinations, along with relevant details about nearby towns, public service facilities, distances, and driving directions. Properly setting up guide signs can not only enhance the efficiency of the road network but also ensure effective communication of infor-

mation. This allows drivers to quickly, accurately, and safely acquire relevant information and choose the optimal driving path.

4.1. Demand Analysis

Highways must meet three core requirements from the drivers' perspective: safety, efficiency, and comfort. Guide signs, as essential tools for conveying information, play a pivotal role in fulfilling these objectives. To ensure optimal performance, several key factors must be considered: (1) Appropriate location: Signs should be placed where drivers can easily spot them. (2) Clear information: The design must allow quick reading and comprehension. (3) Continuity and consistency: Information should flow logically across signs to prevent confusion and ensure smooth navigation. Thus, for highways to deliver safe, efficient, and comfortable journeys, guide signs must exhibit standardization, readability, continuity, and consistency.

Standardization: The proper placement and arrangement of guide signs directly affect the use efficiency of a highway. A well-designed layout can enhance driver comfort by providing effective information at the right moment, preventing confusion due to missing or improperly installed signs. Readability: Clear signage ensures that drivers can quickly obtain information and respond promptly. Poor readability increases the likelihood of risky driving behaviors, such as sudden braking or abrupt lane changes. Continuity: Guide signs should announce upcoming destinations and maintain consistency before and after exits. For instance, exit preview signs should align with the information presented at the exit and at branching points. In distance signs, the first-listed destination should correspond with the upcoming exit's information, ensuring seamless guidance until drivers reach their destination. Consistency: Sign information must remain consistent across the highway network. For instance, the top-listed destination on distance signs should align with corresponding exit preview signs, and mainline exit signs must match their previews. Additionally, toll station signs should correspond with relevant entry and exit signs to ensure smooth, uninterrupted navigation for drivers.

4.2. Influencing Factors Analysis

Through questionnaire surveys and on-site research, it was identified that drivers' key requirements for highway directional signs focus on four aspects: standardization, readability, continuity, and consistency. Further analysis of these requirements revealed multiple influencing factors, which form the basis of the evaluation index system. The influencing factors for these needs are summarized in Table 6.

Table 6. Factors affecting the effectiveness of guide signs.

Guide Sign Effectiveness	Influencing Factors
Standardization	Whether distance signs are set according to requirements
	Whether exit advance and exit confirmation signs are installed
	Completeness of facility guidance along the route
Readability	Compliance of panel colors with standards
	Compliance of panel shapes with standards
	Compliance of fonts with standards
	Whether directional arrows meet standards
	Comfort of sign recognition
	Whether the panel contains excessive information

Table 6. *Cont.*

Guide Sign Effectiveness	Influencing Factors
Readability	Whether there are obstructions blocking the signs
	Condition of the reflective film
	Presence of dirt or damage on the sign panel
	Whether signs are tilted or misaligned
Continuity	Whether information is selected hierarchically
	Whether the information meets drivers' needs
	Whether there are interruptions in guidance information
	Completeness of advance signs
Consistency	Rationality of advance sign information
	Accuracy in reaching the destination
	Effectiveness of route guidance

4.3. Evaluation Metric Determination

Based on the influencing factors listed in Table 6, appropriate evaluation metrics were selected to assess the effectiveness and compliance of guide signs.

4.3.1. Compliance Indicators

To address factors affecting the compliance of guide signs, the following evaluation metrics are proposed.

(1) Conformity rate of distance signs (D_1)

According to the standards, distance signs should be placed more than 1 km after the end of the acceleration lane of an interchange, with repeated signs spaced at intervals of at least 5 km. This metric is defined as the proportion of distance signs meeting these placement standards relative to the total number of signs.

$$D_1 = 1 - g_{11}/G_1 \tag{11}$$

D_1 is the conformity rate of distance signs, g_{11} is the number of distance signs not set according to standards or with incorrect spacing, and G_1 is the total number of required distance signs.

(2) Configuration rate of advance exit signs and confirmation signs (D_2)

Highways must have advance exit signs before interchanges to alert drivers of upcoming exits, and confirmation signs at the exits to verify the destination. This metric is defined as the proportion of interchanges with complete advance and confirmation signage relative to the total.

$$D_2 = 1 - n_1/N \tag{12}$$

D_2 is the configuration rate of advance exit signs and confirmation signs, n_1 is the number of interchanges with incomplete signage, and N is the total number of interchanges.

(3) Completeness rate of facility guide signs (D_3)

Facilities along highways include gas stations, service areas, and parking zones. Appropriate guide signs must be placed before reaching these facilities. This metric is defined as the proportion of facilities with corresponding guide signs relative to the total number Y of facilities.

$$D_3 = 1 - y_{13}/Y \tag{13}$$

D_3 is the completeness rate of facility guide signs. y_{13} is the number of facilities without guide signs.

4.3.2. Readability Indicators

Based on the factors affecting the readability of guide signs, the following evaluation indicators are proposed.

(1) Compliance rate of layout standards (D_4)

This indicator assesses whether guide signs meet standards in design elements like color, shape, font, and directional arrows. For highways and urban expressways, guide signs should have a green background with white symbols, a white border, and green edging, with a square shape. Fonts should primarily be in Chinese, with additional languages or English if needed; English names must follow pinyin rules, capitalizing only the first letter. Up to six types of directional arrows are permitted, including right, diagonal right, straight, and diagonal left. This metric is the proportion of compliant guide signs to total signs.

$$D_4 = 1 - g_{21}/G \tag{14}$$

D_4 is the compliance rate of layout standards, g_{21} is the number of signs that do not meet standards, and G is the total number of guide signs.

(2) Visual comfort of layout (D_5)

The comfort experienced by highway users depends on both the design of the signs and environmental factors. Poor design may increase driver fatigue and elevate the risk of traffic accidents. To assess visual comfort, an attitude scale is applied, with five levels of satisfaction: very satisfied (5 points), satisfied (4 points), neutral (3 points), dissatisfied (2 points), very dissatisfied (1 point). Score = Total score from all questionnaires/(5* number of questionnaires).

(3) Non-overload rate of layout information (D_6)

When the amount of information on a guide sign exceeds recommended limits, drivers may struggle to recognize and process key details in time, potentially compromising safety. According to the standard, the total number of destination entries on a single sign should not exceed six per direction. This indicator is defined as the ratio of signs with non-overloaded information to the total number G of guide signs.

$$D_6 = 1 - g_{22}/G \tag{15}$$

D_6 represents the rate of non-overloaded signage information, while g_{22} denotes the number of overloaded signs.

(4) Unobstructed signage rate (D_7)

Guide signs may be blocked by trees, vegetation, or other structures, impairing visibility and reducing their effectiveness. This indicator is defined as the ratio of guide signs that are not blocked by obstacles to the total number G of guide signs.

$$D_7 = 1 - g_{23}/G \tag{16}$$

D_7 represents the rate of unobstructed signs, while g_{23} denotes the number of obstructed signs in the directional signage.

(5) Intact reflective film rate (D_8)

Reflective films enhance the visibility of guide signs at night, contributing to driver safety. However, signs with faded, cracked, or peeling reflective film reduce visibility and

hinder the communication of critical information. This indicator is defined as the ratio of guide signs with undamaged reflective film to the total number G of guide signs.

$$D_8 = 1 - g_{24}/G \tag{17}$$

D_8 represents the completeness rate of reflective film, while g_{24} denotes the number of directional signs with incomplete reflective film.

(6) Maintenance rate for clean signage (D_9)

Guide signs exposed to outdoor elements are prone to dirt accumulation, which reduces their visibility and effectiveness. Regular maintenance is essential to keep signs legible. This indicator is defined as the ratio of signs free from dirt and damage to the total number G of guide signs.

$$D_9 = 1 - g_{25}/G \tag{18}$$

D_9 represents the maintenance rate of signs with dirt, while g_{25} denotes the number of dirty signs among directional signs.

(7) Alignment accuracy rate (D_{10})

Guide signs may bend or tilt due to wind loads, especially in coastal areas where severe weather is frequent. This indicator is defined as the ratio of guide signs with correct alignment to the total number G of guide signs.

$$D_{10} = 1 - g_{26}/G \tag{19}$$

D_{10} represents the rate of signs positioned correctly, while g_{26} denotes the number of signs that are tilted among the directional signs.

(8) Effectiveness of information retrieval (D_{11})

The goal of guide signs is to provide timely and accurate information to road users. However, the effectiveness of information retrieval can be influenced by the design of signage and external factors. To assess user satisfaction with the ease of information retrieval, a five-level Likert scale is employed, with the following scores: very satisfied (5 points), satisfied (4 points), neutral (3 points), dissatisfied (2 points), very dissatisfied (1 point). Score = Total score/(5* sum of questionnaires).

4.3.3. Continuity Indicators

To address the factors influencing the continuity of guide signs, the following evaluation indicators are proposed.

(1) Reasonableness rate of hierarchical information selection (D_{12})

Information on guide signs should follow the hierarchical structure outlined in the standards, including both advance guide signs and confirmation signs at intersections. This indicator measures the proportion of signs with appropriately selected hierarchical information among all destination distance signs. It is defined as the ratio of signs with appropriately selected hierarchical information to the total number of distance signs.

$$D_{12} = 1 - g_{31}/G_2 \tag{20}$$

D_{12} represents the rate of reasonable selection of information layers; g_{31} denotes the number of signs with unreasonable information layers; G_2 is the total number of distance signs.

(2) Satisfaction with information selection (D_{13})

Given the complexity of highway operations and the varying levels of familiarity drivers have with road conditions, user needs and capacities to process guide sign information may differ based on individual cognitive abilities and physical conditions. Therefore, information selection should strive to meet the diverse needs of road users. To assess user satisfaction with the information provided, a five-level Likert scale is employed, with the following scores: very satisfied (5 points), satisfied (4 points), neutral (3 points), dissatisfied (2 points), very dissatisfied (1 point). Score = Total score/(5* sum of questionnaires).

(3) Continuity rate of guidance information (D_{14})

This indicator assesses interruptions in guidance information along highways. Each interchange is treated as an evaluation unit, measuring the consistency of destination information through destination distance signs. Specifically, it checks the destination consistency from the first row of a distance sign to the advance guide and confirmation signs of the next exit. If the destination information changes before reaching the next exit, it is considered a break in continuity. This indicator is defined as the ratio of uninterrupted interchanges to the total number N.

$$D_{14} = 1 - n_2/N \tag{21}$$

D_{14} represents the continuity rate of guiding information; n_2 denotes the number of interchanges with uninterrupted guidance information.

(4) Completeness rate of advance signs (D_{15})

Advance guide signs must be installed along highways or urban expressways at 2 km, 1 km, 500 m, and at the beginning of the deceleration lane transition section. Each interchange serves as an evaluation unit. The completeness rate is defined as the ratio of interchanges with fully installed advance signs to the total number N of interchanges.

$$D_{15} = 1 - n_3/N \tag{22}$$

D_{15} represents the completeness rate of exit warning signs; n_3 denotes the number of interchanges with incomplete exit warning signs.

4.3.4. Consistency Indicators

The factors influencing the consistency of guide signs primarily include the reasonableness of the advisory sign information, the accuracy of reaching destinations, and the effectiveness of path guidance. The following evaluation indicators are proposed to assess these factors.

(1) Reasonableness rate of exit advisory sign layout (D_{16})

Exit advisory signs should display an exit number and follow a two-line format: the first line shows the highway number or name, while the second lists a notable location along that route. Signs lacking an exit number or with disorganized information fall short of layout standards. This indicator measures the proportion of exit advisory signs with a compliant layout relative to the total number of such signs.

$$D_{16} = 1 - g_{41}/G_3 \tag{23}$$

D_{16} represents the rationality rate of the layout of exit warning signs; g_{41} denotes the number of exit warning signs with unreasonable layouts; G_3 is the total number of exit warning signs.

(2) Consistency rate of directional signs (D_{17})

This indicator evaluates the coherence and consistency of directional signage across road segments to ensure drivers receive accurate, continuous guidance. Inconsistent information—such as differing destinations on distance versus exit signs—can cause confusion, misjudgment, and missed exits. The consistency rate measures how well information aligns between successive signs, facilitating smooth and safe travel. It is defined as the proportion of the number of straight-ahead signs where the next exit information matches the second-line location information on the previous distance sign to the total number G_4 of exit straight signs at interchanges.

$$D_{17} = 1 - g_{42}/G_4 \tag{24}$$

D_{17} represents the consistency rate of directional signs; g_{42} denotes the number of non-corresponding exit straight signs.

(3) Appropriateness of route guidance effect (D_{18})

This indicator assesses the effectiveness of route guidance for road users, which is a core function of directional signage. It reflects whether drivers, under the guidance of these signs, can smoothly reach their intended destinations and whether the suggested route is the most optimal. To quantify the effectiveness of route guidance, an attitude-based rating method is applied. User satisfaction is divided into five levels: very satisfied (5 points), satisfied (4 points), neutral (3 points), dissatisfied (2 points), very dissatisfied (1 point). Score = Total score/(5* sum of questionnaires).

4.4. Framework of the Evaluation Indicator System

Based on the analysis of the issues present in directional signs, four key areas of demand have been identified. Corresponding evaluation indicators have been established based on these needs, leading to the creation of a comprehensive evaluation indicator system for guide signs, as illustrated in Figure 2.

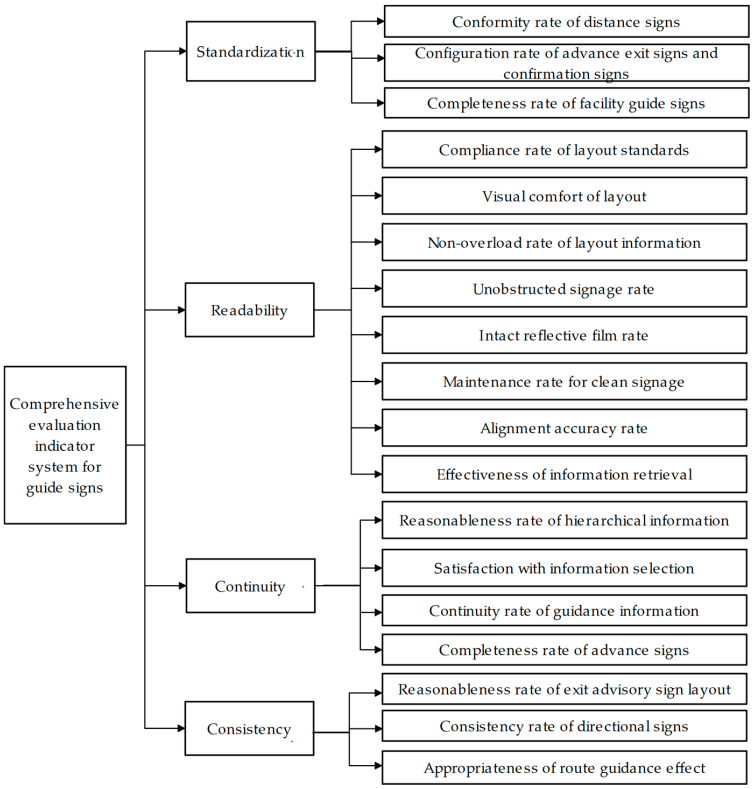


Figure 2. Evaluation index system for guide signs.

5. Evaluation Model and Application

In the evaluation indicator system for highway guide signs, the proximity of each indicator's quantified results to its ideal value directly reflects the effectiveness of guide sign placement. This "proximity to ideal solution" characteristic aligns perfectly with the core concept of the TOPSIS method. By calculating the distances between evaluated objects and the positive/negative ideal solutions, TOPSIS can precisely measure how closely guide sign configurations approach the ideal standard, thereby enabling scientific evaluation of their effectiveness. Consequently, this study employs the TOPSIS method to construct the evaluation model, ensuring the objectivity and accuracy of assessment results.

5.1. Construction of the Evaluation Model Based on the TOPSIS Method

5.1.1. Evaluation Model Construction

From the previous analysis, it is evident that the evaluation system for guide signs is divided into two levels. The primary indicators include the normative nature of guide signs (B1), the readability of guide signs (B2), the continuity of guide signs (B3), and the consistency of guide signs (B4). These indicators evaluate the effectiveness of guide sign settings from four aspects of demand. By analyzing the influencing factors of each demand aspect, corresponding secondary evaluation indicators are proposed, thereby constructing a structural model for assessing the effectiveness of guide signs, as shown in Figure 3.

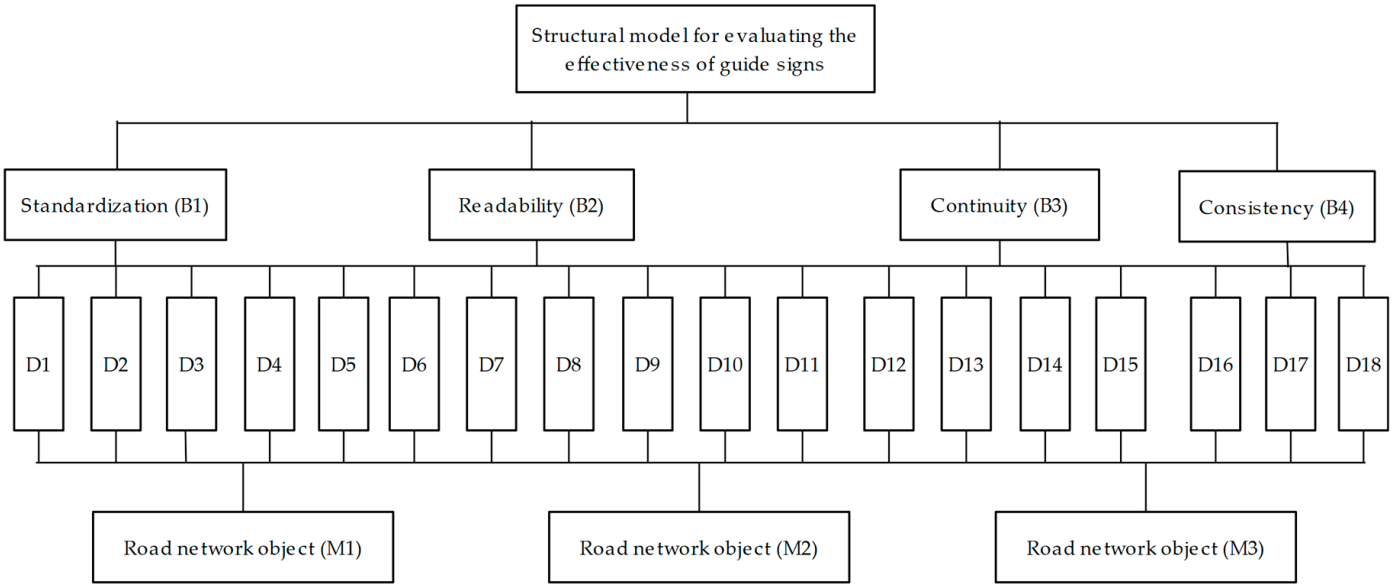


Figure 3. Structural model for evaluating guide sign effectiveness.

5.1.2. Evaluation Procedure

The evaluation of highway guide signs follows a structured approach based on the previously established indicators and evaluation model. The steps are as follows:

(1) Collection of background data

Gather relevant basic information about the evaluated road, including its classification, number of lanes, road alignment, geometric conditions, and intersections.

(2) Development of a survey plan

Define a detailed survey strategy. Subjective indicators: Use questionnaires focusing on driver behavior and needs to collect relevant data. Objective indicators: Conduct field research to obtain real-world data on the guide signs along the road.

(3) Implementation of field surveys

Execute the survey plan as designed: Conduct subjective surveys by distributing questionnaires to drivers at highway service areas to gather feedback for subjective metrics. For objective data, surveyors drive along the highway section under evaluation, using direct observation and video recordings to collect data on the guide signs.

(4) Calculation of evaluation indicators

Classify the collected data based on the indicator categories. Compute each indicator using the formulas provided in the research framework.

(5) Evaluation of the objects

Apply the TOPSIS method to assess the effectiveness of the guide signs on the highway, determining how well they meet optimal standards. There are seven specific steps, as follows:

(a) Formulate the decision matrix. In the evaluation of road network signage, let $M = (M1, M2, \cdots, M_m)$ represent the set of evaluation objects and $D = (D1,\ D2, \cdots,\ D_n)$ represent the set of indicators. The value of an evaluation object M_i concerning an indicator D_j is denoted as $x_{ij}(i = 1, 2, \ldots, m; j = 1, 2, \ldots, n)$. Thus, the decision matrix X is structured as follows:

$$X = \begin{pmatrix} & D_1 & D_2 & \ldots & D_n \\ M_1 & x_{11} & x_{12} & \ldots & x_{1n} \\ M_2 & x_{21} & x_{22} & \ldots & x_{2n} \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ M_m & x_{m1} & x_{m2} & \ldots & x_{mn} \end{pmatrix} \tag{25}$$

(b) Normalization of indicators. To eliminate the impact of differing dimensions among evaluation indicators on decision-making, normalization is applied to the data. Indicators are classified into two categories based on their nature: high-priority indicators (where larger values are better) and low-priority indicators (where smaller values are better). Different normalization algorithms are used for these two types of indicators.

$$x'_{ij} = \begin{cases} \frac{x_{i,j} - \min\{x_{i,j}, x_{2,j}, \cdots, x_{m,j}\}}{\max\{x_{i,j}, x_{2,j}, \cdots, x_{m,j}\} - \min\{x_{i,j}, x_{2,j}, \cdots, x_{m,j}\}}; \text{high} - \text{priorityindicators} \\ \frac{\max\{x_{i,j}, x_{2,j}, \cdots, x_{m,j}\} - x_{i,j}}{\max\{x_{i,j}, x_{2,j}, \cdots, x_{m,j}\} - \min\{x_{i,j}, x_{2,j}, \cdots, x_{m,j}\}}; \text{low} - \text{priorityindicators} \end{cases} \tag{26}$$

(c) Determine the weights of each indicator. The Analytic Hierarchy Process (AHP) is employed to perform pairwise comparisons of each indicator's importance relative to the corresponding criteria at the upper level. This method helps in establishing the relative weights of the indicators and conducting a consistency check to verify their coherence.

(d) Construct the weighted decision matrix. Multiply the weights of each indicator by the non-dimensional matrix to obtain the weighted decision matrix $R = \left(r_{ij}\right)_{m \times n}$ for the directional signs. This matrix reflects the importance of each indicator in relation to the overall assessment, allowing for a more informed evaluation of the directional signs' effectiveness.

$$r_{ij} = W_j * x'_{ij},\ (i = 1, 2, \cdots, m, j = 1, 2, \cdots, n) \tag{27}$$

(e) Determine the optimal and worst solutions. The optimal solution S^+ is formed by the maximum values of each column in matrix R.

$$S^{+} = \begin{cases} (\max r_{i1}, \max r_{i2}, \cdots, \max r_{in}); D_j \text{ is a "larger is better" type indictor} \\ (\min r_{i1}, \min r_{i2}, \cdots, \min r_{in}); D_j \text{ is a "smaller is better" type indictor} \end{cases} (1 \le i \le m) \quad (28)$$

The worst solution s^{-} is formed by the minimum values of each column in matrix R.

$$S^{-} = \begin{cases} (\min r_{i1}, \min r_{i2}, \cdots, \min r_{in}); D_j \text{ is a "larger is better" type indictor} \\ (\max r_{i1}, \max r_{i2}, \cdots, \max r_{in}); D_j \text{ is a "smaller is better" type indictor} \end{cases} (1 \le i \le m) \quad (29)$$

(f) Calculate the distance of each option from the optimal and worst solutions. At this point, use the Euclidean distance to calculate the distance Sd_i^{+}, Sd_i^{-} from the optimal and worst solution.

$$Sd_i^{+} = \sqrt{\sum_{j=1}^{n} (s^{+} - r_{ij})^2}, \ i = 1, 2, \cdots, m \quad (30)$$

$$Sd_i^{-} = \sqrt{\sum_{j=1}^{n} (s^{-} - r_{ij})^2}, \ i = 1, 2, \cdots, m \quad (31)$$

(g) Calculate the closeness of each solution to the optimal solution C_i as follows:

$$C_i = \frac{Sd_i^{-}}{Sd_i^{-} + Sd_i^{+}}, \ i = 1, 2, \cdots, m \quad (32)$$

The larger the value of C_i, the closer the decision-making solution is to the optimal solution, indicating a better overall solution.

5.1.3. Practical Analysis of Evaluation Results

The application of evaluation results can be divided into two scenarios:

(1) Single object evaluation

The evaluation indicators are divided into three categories: standardized indicators, optimizable indicators, and subjective indicators (as shown in Table 7). Among them, the value of the standardized indicator should be 1, which is a mandatory standard requirement in the Chinese logo specification. The requirements are relatively strict, and if the rating value is lower than 0.95, it must be rectified. There is no clear requirement for optimizable indicators in Chinese signage standards, but they are still relatively important in terms of guidance effectiveness. If the score is below 0.9, rectification is needed. Subjective indicators reflect the feelings of road users, which are not explicitly required in Chinese signage standards. However, the driving experience of drivers is also relatively important. If the rating value is below 0.9, it also needs to be rectified.

(2) Comparison of two objects (e.g., before and after adjustments)

By comparing the scores before and after adjustments, the effectiveness of the optimization can be evaluated: If the post-adjustment score is higher than the pre-adjustment score, the improvement was successful. If the score decreases after the adjustment, it indicates that the changes negatively impacted performance.

The specific rectification standards and measures can be flexibly designed based on the project's context to ensure that the guide signs meet both safety and guidance needs, improving the overall highway user experience.

Table 7. Evaluation indicator categories.

Indicator Category	Evaluation Indicators
Standardizable indicators	Compliance rate for distance sign configuration
	Configuration rate for exit advance and confirmation signs
	Completeness rate of facility guidance signs
	Compliance rate with layout standards
	Non-overload rate of layout information
	Rational selection rate of hierarchical information
	Completeness rate of advance signs
	Reasonable layout rate of exit advance signs
	Consistency rate of directional signs
Optimizable indicators	Obstruction-free rate of sign placement
	Completeness rate of reflective films
	Maintenance rate of signs against damage
	Correct alignment rate of signs
	Continuity rate of guiding information
Subjective indicators	Visual comfort of the layout
	Effectiveness of information retrieval
	Satisfaction with information selection
	Appropriateness of route guidance

5.2. Application of the Evaluation Model

The G2 Expressway in China, a major north–south arterial route, connects Beijing to Shanghai and passes through key cities in Hebei Province, such as Langfang and Cangzhou. Through the investigation of existing traffic signs on the G2 expressway mentioned earlier, it was found that this section has significant high traffic flow characteristics. It is worth noting that a questionnaire survey and in-depth interviews with high-frequency drivers on this section revealed that the Hebei section of the G2 Expressway intersects with 11 typical roads, with a large number of traffic sign samples (involving 11 typical sections), and a large number of sign facilities do not comply with standard specifications. Based on this, in order to effectively verify the practical application effectiveness of the traffic sign evaluation model constructed in this article, the research team selected the Hebei section of the G2 Expressway, including its intersections with 11 other highways (e.g., G3, G2501, and G18), as the empirical research object, focusing on the technical evaluation of the standardization of its sign system. A total of 558 traffic guide signs were surveyed along the selected segment, with 99 signs failing to meet the relevant requirements for guide signage. In addition, for subjective indicators (D5, D11, D13, and D18), on-site questionnaires were administered to collect drivers' evaluations of the signage's effectiveness. After filtering out invalid responses, the corresponding indicator values were calculated. Microsoft Excel (Version 2019) was utilized for the computational processes of the TOPSIS method. The evaluation results for all indicators are summarized in Table A4 (see Appendix A).

From Table A4, it can be seen that the issues with traffic signs are layout specification problems (58), sign occlusion problems (21), and layout information overload problems (18). The number of problematic traffic signs corresponding to different evaluation indicators varies greatly, which reflects the actual situation of traffic signs on this highway.

(1) Forming the decision matrix

In the evaluation of the G2 Hebei section's signage indicators, the optimal value for all indicators is set to 1, while the worst value is set to 0. All optimal indicator values are treated as an optimal set (denoted as M1), and all worst indicator values are treated as a worst set (denoted as M2). The actual indicator values from the road network form the actual set (denoted as M3). Thus, the decision matrix X is formed, and normalization is applied to X to obtain standardized values.

$$X = \begin{bmatrix} 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0.95 & 1 & 0.92 & 0.9 & 0.8 & 0.97 & 0.96 & 1 & 1 & 0.99 & 0.92 & 0.9 & 0.77 & 0.93 & 0.82 & 0.9 & 1 & 0.85 \end{bmatrix}$$

(2) Determining the weights of indicators

(a) Determining the weights of primary indicators: Using the AHP, pairwise comparisons are made to evaluate the relative importance of the primary indicators. The pairwise comparison matrix constructed for evaluating the effectiveness of highway signage is shown in Table A5 (see Appendix A).

In the primary indicators, the normativity and compliance are the fundamental requirements. More importantly, continuity and consistency are pursued only after ensuring normative and compliance standards are met. Therefore, normative and compliance aspects are relatively more significant. After data processing, the weights of each primary indicator are as shown in Table A6 (see Appendix A).

The values of CI and CR in the table are both less than 0.1, indicating that the consistency check is satisfied.

(b) Determining the weights of secondary indicators: Within the primary indicator of "Normativity", the three indicators—location distance sign, exit notification confirmation sign, and guidance sign for roadside facilities—are primarily concerned with whether they are set up correctly. Since these three indicators are of equal importance, their weights relative to the higher-level objective are also equal, as shown in Table A7 (see Appendix A).

The weights for the secondary indicators corresponding to the other three primary indicators (Readability, Continuity, and Consistency) are also determined using the AHP. Pairwise comparisons are made regarding the importance of these indicators in relation to their respective primary indicators. The comparison matrices are constructed as shown in Tables A8–A10 (see Appendix A), in accordance with the standards outlined.

The summary of the weighted values for all secondary indicators of expressway signage after data processing is shown in Table A11 (see Appendix A). The values of CI and CR in the table are both less than 0.1, indicating that the consistency check is satisfied.

(c) Constructing the weighted decision matrix

Multiply the weights of each indicator by the dimensionless matrix to obtain the weighted decision matrix for the road signs R.

$$R = \begin{bmatrix} 0.15 & 0.15 & 0.15 & 0.05 & 0.01 & 0.05 & 0.03 & 0.01 & 0.02 & 0.03 & 0.05 & 0.02 & 0.1 & 0.01 & 0.06 & 0.04 & 0.2 & 0.1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0.14 & 0.15 & 0.14 & 0.05 & 0.01 & 0.05 & 0.03 & 0.01 & 0.02 & 0.03 & 0.05 & 0.02 & 0.07 & 0.01 & 0.05 & 0.04 & 0.2 & 0.1 \end{bmatrix}$$

(d) Determining the optimal and worst solutions

In this evaluation case, the optimal value for each indicator is 1, which defines the optimal solution as optimal solution $S^+ = M_1$. Similarly, the worst value for each indicator is 0, defining the worst solution as worst solution $S^- = M_2$. Calculate the distance between solution M_3 and the optimal solution S^+ and the worst solution S^-, respectively.

$$Sd_3^+ = 0.0332 \;\; Sd_3^- = 0.3448$$

The relative closeness C_3 of the solution M_3 to the optimal solution S^+ is

$$C_3 = \frac{0.3448}{0.0332 + 0.3448} = 0.9121$$

Therefore, the final evaluation indicates that the closeness of this solution to the optimal solution is 0.9121.

The effectiveness evaluation of the G2 Expressway's guide signs indicates room for improvement. Six evaluation metrics scored below 0.9: layout compliance rate, visual comfort of spatial arrangement, rational selection rate for hierarchical information, user satisfaction with information prioritization, completeness of advance signage, and appropriateness of route guidance. These findings suggest a need to revise layout standards and enhance advance signage configuration to ensure regulatory compliance. Furthermore, three subjective indicators (i.e., visual comfort, satisfaction with information selection, and appropriateness of route guidance) directly reflect drivers' subjective experiences. This underscores the necessity of optimizing the signage system with a user-centric approach to improve operational usability. Case validation demonstrates that the proposed evaluation method effectively assesses expressway signage performance while providing actionable recommendations for optimization. Such improvements can enhance both traffic safety compliance and user experience outcomes.

6. Discussion and Conclusions

Highway direction signs are vital for safety and navigation, yet field research reveals significant practical challenges. Drivers struggle with cluttered information, inconsistent placement, and poor visibility. To address these, we propose a TOPSIS-based evaluation model focusing on four key needs: normativity (compliance with standards), readability (clear content hierarchy), continuity (logical advance signage), and consistency (uniform symbols). In the actual management and operation of highways, this comprehensive evaluation model demonstrates significant practical value. Taking the busy highway interchange areas on urban outskirts as an example in this study, the model quantitatively analyzes core indicators such as sign standardization, visibility, continuity, and consistency, accurately identifying issues such as missing or discontinuous information at certain interchange ramp exits. These issues often lead to driver misjudgment in complex traffic conditions. Based on the risk warning list generated by the model, management authorities swiftly formulated a prioritized renovation plan, supplementing missing exit warning signs and standardizing terminology across multiple zones to ensure consistent information presentation. The main findings of this study are summarized as follows:

(1) The questionnaire and field research indicate that, from the drivers' subjective perspective, there are challenges such as difficulties in information retrieval, unclear sign content, and complex graphics. From a regulatory standpoint, issues include non-compliant font sizes, information overload, missing advance signs, unreasonable placements, insufficient hierarchy, and lack of continuity. Analysis of the survey responses reveals that drivers prioritize safety, efficiency, and comfort in their journeys. Based on the role of direction signs, it is suggested that drivers require signs to exhibit

normativity, readability, continuity, and consistency, with a definition and analysis of these four types of needs provided.

(2) Based on drivers' needs regarding highway direction signs, factors influencing these needs were analyzed, leading to the design of corresponding evaluation indicators. The evaluation is proposed at interchange units, assessing normativity, visibility, continuity, and consistency, and quantifying these indicators to construct a comprehensive evaluation system.

(3) By analyzing the evaluation indicator system and comparing various comprehensive evaluation methods, the TOPSIS method was selected for evaluating the effectiveness of highway direction signs. Selecting the Hebei section of the G2 expressway as a case study, it was demonstrated that the proposed evaluation index system and model are feasible and can be used for the comprehensive evaluation of highway directional signs.

From a traffic management perspective, the model facilitates a shift from traditional reactive maintenance to a proactive, dynamic prevention approach. It enables authorities to anticipate and address potential issues in advance, improving the scientific rigor and foresight of traffic management. For drivers, the optimized signage system provides clearer and more accurate guidance, reducing confusion and misjudgment during driving, mitigating fatigue and accident risks, and ultimately enhancing the travel experience. From an industry development standpoint, the model's evaluation framework lays a solid foundation for updating sign design standards. It clarifies critical metrics such as information density thresholds and graphic simplification principles, promoting more standardized, uniform, and user-friendly highway sign design. This elevates the overall service quality and operational efficiency of the road traffic system, providing robust support for building a safer, more efficient, and convenient transportation environment.

In future research, we will add multiple highways of different types and scenarios to collect traffic sign data for further testing and evaluation of the model. Meanwhile, several key areas can be further explored: (1) User-centric factors: Future research should thoroughly consider the individual differences among road users and how these variances affect the effectiveness of highway direction signs. This includes studying demographic factors, driving experience, and cognitive load, and exploring strategies to mitigate the negative impacts of these differences on sign usability. (2) External environmental factors: In evaluating the use of highway direction signs, it is essential to take into account external factors such as road alignment, traffic volume, other vehicles, and weather conditions. Research should focus on how to integrate these variables into the evaluation methods and correct their effects on assessment results. This may involve developing adaptive models that can dynamically adjust to changing conditions, ensuring a more accurate reflection of sign effectiveness under varying circumstances.

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Abbreviations

TOPSIS	Technique for Order Preference by Similarity to an Ideal Solution
KMO	Kaiser–Meyer–Olkin
AHP	Analytic hierarchy process
CRITIC	Criteria Importance Through Intercriteria Correlation
EM	Entropy method
CI	Consistency index
RI	Random consistency index
CR	Consistency ratio
FCE	Fuzzy comprehensive evaluation
GRA	Grey relational analysis
DEA	Data envelopment analysis
FA	Factor analysis

Appendix A

(1) Tables in the questionnaire survey

Table A1. Guidance tools preferred while driving (ranked by importance).

Guidance Tool	N	Range	Min	Max	Mean	Std. Dev.
Vehicle navigation	129	3	1	4	1.24	0.547
Guide signs	124	3	1	4	1.53	0.761
Maps	78	3	1	4	1.56	0.934
Asking locals	42	3	1	4	3.29	0.970

Table A2. Main problems with highway guide signs (ranked by importance).

Issue Description	N	Range	Min	Max	Mean	Std. Dev.
Missing useful information	115	5	1	6	1.63	1.224
Poor visibility	75	5	1	6	1.75	1.480
Complicated graphics	72	5	1	6	1.82	1.346
Information overload	72	4	1	5	2.14	1.282
Inconvenient placement	69	5	1	6	2.71	1.373
Blocked by trees	46	5	1	6	3.17	1.755

Table A3. Main types of information utilized from guidance signs (multiple choices).

Information Type	Participant Count	Total Response Percentage	Participant Percentage
Names of reachable destinations	177	36.0%	75.0%
Names of reachable highways	147	29.9%	62.3%
Current highway name	64	13.0%	27.1%
Current location name	69	14.1%	29.2%
Shape of the intersection highway ahead	33	6.7%	14.0%
Distance to upcoming highway or location	1	0.2%	0.4%
Total	491	100.0%	208.1%

(2) Tables in model application cases

Table A4. Survey data and evaluation values for each indicator.

Primary Indicators	Secondary Indicators	Number of Issues	Total Samples	Indicator Value
Compliance (B_1)	Location distance compliance rate (D_1)	2	38	0.9474
	Pre-exit and confirmation sign rate (D_2)	0	11	1
	Complete guide sign ratio (D_3)	3	37	0.9189
Readability (B_2)	Conformance to layout standards (D_4)	58	558	0.8961
	Visual comfort (D_5)	-	-	0.81
	Non-overloaded information rate (D_6)	18	558	0.9677
	Unobstructed sign placement rate (D_7)	21	558	0.9624
	Reflective film integrity rate (D_8)	0	558	1
	Maintenance of sign cleanliness (D_9)	2	558	0.9964
	Correct sign angle rate (D_{10})	5	558	0.991
	Effectiveness of information retrieval (D_{11})	-	-	0.92
Continuity (B_3)	Rational layered information rate (D_{12})	4	38	0.8947
	Satisfaction with information selection (D_{13})	-	-	0.77
	Continuity of route guidance rate (D_{14})	1	11	0.9286
	Completeness of advance signs (D_{15})	2	11	0.8182
Consistency (B_4)	Reasonable layout for pre-exit signs (D_{16})	3	33	0.9091
	Information consistency rate (D_{17})	0	10	1
	Appropriateness of route guidance (D_{18})	-	-	0.85

Table A5. Pairwise comparison matrix of primary indicators.

A	B_1	B_2	B_3	B_4
B_1	1	2	3	3
B_2	1/2	1	2	2
B_3	1/3	1/2	1	2
B_4	1/3	1/2	1/2	1

Table A6. Primary indicator weights.

	B_1	B_2	B_3	B_4
W^0	0.4495	0.2596	0.1707	0.1202
λmax	4.0716			
CI	0.02386			
RI	0.89			
CR	0.0268			

Table A7. Weights of secondary indicators corresponding to "Normativity".

Primary Indicator	Secondary Indicator	Relative Weight W^0	Total Weight W_j
Normativity	D_1	0.333	0.1498
	D_2	0.333	0.1498
	D_3	0.333	0.1498

Table A8. Comparison matrix for secondary indicators corresponding to "Readability".

B_2	D_4	D_5	D_6	D_7	D_8	D_9	D_{10}	D_{11}
D_4	1	4	1	2	4	3	2	1
D_5	1/4	1	1/3	1/2	1/2	1/2	1/3	1/3
D_6	1	3	1	2	3	2	2	1
D_7	1/2	2	1/2	1	2	2	1	1/2
D_8	1/4	2	1/3	1/2	1	1/2	1/3	1/4
D_9	1/3	2	1/2	1/2	2	1	1/2	1/2
D_{10}	1/2	3	1/2	1	3	2	1	1/2
D_{11}	1	3	1	2	4	2	2	1

Table A9. Comparison matrix for secondary indicators corresponding to "Continuity".

B_3	D_{12}	D_{13}	D_{14}	D_{15}
D_{12}	1	1/4	2	1/3
D_{13}	4	1	8	2
D_{14}	1/2	1/8	1	1/5
D_{15}	3	1/2	5	1

Table A10. Comparison matrix for secondary indicators corresponding to "Consistency".

B_4	D_{16}	D_{17}	D_{18}
D_{16}	1	1/4	1/3
D_{17}	4	1	2
D_{18}	3	1/2	1

Table A11. Weights of secondary indicators.

Total Objective	Primary Indicator	Secondary Indicator	Relative Weight	Total Weight	Max	CI	RI	CR
A	B_1	D_1	0.333	0.1498	8.1651	0.0236	1.41	0.0167
		D_2	0.333	0.1498				
		D_3	0.333	0.1498				
	B_2	D_4	0.208	0.0539				
		D_5	0.048	0.0125				
		D_6	0.185	0.0481				
		D_7	0.109	0.0282				
		D_8	0.056	0.0144				
		D_9	0.081	0.0211				
		D_{10}	0.121	0.0315				
		D_{11}	0.192	0.0498				
	B_3	D_{12}	0.118	0.0217	4.0155	0.0052	0.89	0.0058
		D_{13}	0.517	0.0954				
		D_{14}	0.061	0.0113				
		D_{15}	0.304	0.0560				
	B_4	D_{16}	0.123	0.0391	3.0183	0.0092	0.52	0.0176
		D_{17}	0.557	0.1776				
		D_{18}	0.320	0.1021				

Table A12. Factor loadings.

Indicators	Standardization	Readability	Continuity	Consistency	Communality
D_1	0.82	0.10	0.05	−0.03	0.69
D_2	0.78	0.08	0.12	0.07	0.64
D_3	0.75	−0.05	0.20	0.10	0.62
D_4	0.05	0.80	0.04	0.03	0.65
D_5	0.08	0.65	0.18	0.04	0.46
D_6	0.06	0.60	−0.10	0.08	0.38
D_7	−0.12	0.55	0.05	−0.08	0.32
D_8	0.10	0.50	0.25	−0.04	0.31
D_9	0.04	0.45	0.12	0.06	0.30
D_{10}	−0.05	0.45	0.10	0.04	0.30
D_{11}	0.08	0.12	0.85	0.04	0.75
D_{12}	0.18	−0.02	0.80	0.10	0.68
D_{13}	0.10	0.08	0.78	0.15	0.65
D_{14}	0.03	0.05	0.70	−0.03	0.50
D_{15}	0.20	0.10	0.65	0.08	0.47
D_{16}	0.05	0.03	0.08	0.88	0.78
D_{17}	0.10	−0.06	0.12	0.82	0.70
D_{18}	0.04	0.08	0.06	0.75	0.57
Eigenvalue	4.20	3.70	2.90	2.05	
Variance explained%	20.0%	17.6%	13.8%	9.8%	
Cumulative variance%	20.0%	37.6%	51.4%	61.2%	

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