Hindawi
Journal of Advanced Transportation
Volume 2022, Article ID 7693492, 15 pages
https://doi.org/10.1155/2022/7693492

Research Article

Information Volume Threshold for Graphical Variable Message Signs Based on Drivers' Visual Cognition Behavior

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Received 8 August 2022; Revised 10 November 2022; Accepted 29 November 2022; Published 10 December 2022

Academic Editor: Socrates Basbas

Variable message signs (VMS) are widely employed to offer drivers dynamic traffic information. However, it is still lacking practical guidance about the information volume displayed on a graphical VMS. Building on the result of the subjective questionnaire survey, a static cognitive experiment was conducted to analyze the influence of volume information (i.e., elements and displaying the number of roads) of graphical VMS on drivers' visual cognition characteristics and then determine the threshold number of roads displayed on VMS. Forty-five drivers participated in the static cognitive experiment. Five indicators, including visual cognition time, cognition accuracy, comprehension accuracy, general assessment, and information acceptance, were used to estimate the influences of graphical VMS. Study results by descriptive statistics and statistical hypothesis testing indicated that drivers also preferred auxiliary elements (i.e., distance or time information) besides basic design elements (i.e., driving direction, current position, and road name) displayed on graphical VMS. With the increase in information volume, driver visual cognition time increased while other companion indexes (i.e., visual cognition accuracy and comprehension accuracy) generally worsened. Combining the data of drivers' objective behavior and subjective scoring, the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) method revealed that the number of roads shown on the graphical VMS should be no greater than five. The study results were verified by dynamic simulation experiments. This finding provides a supplement for the design standards and usage specifications for VMS.

1. Introduction

Variable message signs (VMS) are widely used on urban roadways and highways. As a terminal device for releasing traffic information, VMS have advantages over static traffic signs, such as providing road users with real-time traffic conditions in the form of graphics or text [1]. Additionally, drivers can determine their routes with the help of real-time road conditions provided by VMS. Information provided by VMS can also help improve driving behavior and safety [2]. Furthermore, road network traffic load optimization and alleviation of traffic pressure can be achieved by VMS through the distribution of driving routes [3].

According to the statistical results reported by the Beijing Institute of Transportation Engineering [4], a total of 414 VMS have been installed on Beijing highways and 87 are scheduled for the future. The growth rate of VMS is expected to increase in the next few years. At the administrative level, roads in China are classified into national roads, provincial roads, and county roads. In Beijing, there are 86 VMS installed on national roads, 202 on provincial roads, and 126 on county roads. Installations include T-shaped columns, overhead gantries, and road-side single cantilevers; the road-side cantilever type accounts for the largest proportion. Sizes of VMS are variable, including 2×4 m, 1.92×0.96 m, and 1×10 m [4].

Functionally, VMS fall between static guide signs and mobile phone navigation. Information given by VMS includes traffic conditions, route guidance, speed limits, and weather. In comparison with text VMS, graphical VMS typically uses graphics as the focus, with text to enhance traffic information (see Figure 1), which has advantages in different forms of content and clear expression. The previous study found that graphical information was more easily recognized by drivers than text information and is not limited by language [5]. Besides, the visible distance of graphical information was also found to be greater [5]. However, compared to a single form of information, drivers preferred to receive information through a combination of text and graphics [6]. VMS displays the traffic conditions of each section of the road network through a combination of graphics and text, which not only benefits drivers choose the appropriate route but also provides information such as the remaining traffic capacity of the entire road network [7]. Currently, there are 355 VMS available to display graphical information on Beijing highways [4].

Figure 1: Example of graphical variable message signs in Beijing.

Although graphical VMS are widely used, some problems still exist in practical applications. According to an investigation of VMS in Beijing conducted by the Beijing Municipal Commission of Transport [4], the main problem is that information displayed on VMS is not easy to understand, making it less useful for drivers. To the best of our knowledge, there are two main reasons for this: (1) there are few specifications for designing VMS and the traffic regulations concerning graphical VMS are insufficient in China and (2) only functions, display methods, positioning, and colors are specified in detail [8–10]. In addition, the existing standards focus on the structure, content, and mode of traffic information displayed on VMS, but there are still unclear provisions on graphic information volume [9, 10]. As a result, there are some problems, such as the lack of a basis for the application settings and display contents, and information overload in design elements. Moreover, few theoretical references for application settings can be found, as there has been insufficient research on graphical VMS in China.

In previous years, some VMS text guidelines and specifications have been proposed. In China, the display mode, setting position, the structure of the message, the text attributes (e.g., font, height, and color), and graphical information of the VMS have been specified [9, 10]. Relevant studies have shown 8–12 words for large VMS and four words for small VMS are specified for road-condition information [8]. Public notice information should be no more than 20 words [9]. In the United States, the Manual on Uniform Traffic Control Devices (MUTCD) also specifies the scope of VMS applications, information display requirements, and text-setting requirements [11]. However, graphical VMS regulations are still insufficient, especially lacking practical guidance about the information volume displayed on a graphical VMS.

In addition to guidelines and specifications, research concerning text VMS is plentiful. According to visual theory and the results of simulation experiments, it was found that drivers have the best visual cognition of boldface characters [12]. A previous study stated that the ratio of text height to dynamic visual cognition distance should be 1 : 300, according to ergonomics theory [13]. Furthermore, through simulation and actual road experiments, it was found that the visual cognition of LED VMS was better than that of reverse reflection VMS [14].

Cognitive load theory indicates that a human's ability to process information is limited and can only process limited information at the same time. Once it exceeds the capacity, the cognitive overload will occur [15]. Additional cognitive and driving loads may be added when drivers perceive traffic signs [16]. The amount of information is positively correlated with the time drivers in searching for the useful information [17]. It is apparent that a driver viewing VMS with too much information needs to slow down to make up for excessive visual cognition time. Moreover, changes in driving speed caused by visual cognition time may increase the possibility of a traffic accident [18]. Hence, inappropriate design and setting of VMS may confuse drivers. An appropriate amount of information helps maximize the effectiveness of VMS and also provides more time for drivers to operate vehicles safely. However, there is little research on the information threshold of graphical VMS.

Both dynamic VMS and static traffic signs display information in the form of graphics and text, so the method of studying traffic signs still has some adaptability for the study of VMS. Typical methods including psychology, ergonomics, and information entropy are usually applied to explore the information threshold of traffic signs [19, 20]. Based on a visual information acquisition experiment, studies have shown that drivers cannot receive VMS information completely when the amount of static VMS is slightly overloaded [21]. Among these studies, static cognitive experiments have been a popular approach for exploring the influence of traffic sign information on drivers' cognitive load.

Although there have been studies exploring information on VMS, they have focused mainly on text VMS. There are few quantitative methods to determine the information threshold of graphical VMS. As graphical VMS have been widely applied on roadways to guide traffic, a suitable information volume for a positive effect on driver behavior must be determined. As the vision was the main way for drivers to capture information about traffic signs [22], driver visual behavior and its degradation should be considered to evaluate the reasonability of graphical VMS. Based on similar studies, static cognitive experiments can accurately record visual cognition behavior for different information volumes [20]. Thus, it is desirable to study the information threshold of graphical VMS scientifically through a static cognitive experiment. The cost of a static experiment is lower than the cost of a dynamic simulation experiment. In addition, static laboratory experiments are safe in comparison with field tests and do not pose any danger to participants. A previous study demonstrated that drivers' eyesight in motion was a little different from the static status if the driving speed is not more than 120 km/h [23].

The current study focuses on determining the optimal information volume for graphical VMS from the perspective of driver visual cognition behavior through a static cognitive experiment. Moreover, the dynamic simulation experiment was conducted to verify the static cognitive experiment results. The study results address information overload on VMS and provide a foundation for improving guidance and specifications for VMS to promote the effectiveness of VMS in practice.

2. Methods

2.1. Participants. A total of 45 drivers, 29 male and 16 female, participated in the experiment. Participants were recruited by public announcement. Each driver must have a Chinese class C driver's license. Participants' age and driving age ranged from 22 to 55 years (average (AVG) = 36.8, standard deviation (SD) = 11.6) and 2 to 30 years (AVG = 12.8, SD = 10.5), respectively. All participants were required to have normal vision or corrected vision above 4.8 (E-shaped visual acuity chart) and to be in a good mental condition. Alcohol and stimulant drugs for two hours before the experiment were prohibited. After completing the driving task, each participant was offered Chinese Yuan (CNY) 150 in cash as a reward. All the experimental procedures were performed following the current laws and guidelines in China. The basic information about the subjects is shown in Table 1.

The current study referenced the following previous study's sample selection experience for static cognition experiments to determine a reasonable sample size. The influence of the amount of information on combined traffic signs was studied with 40 drivers [24]. In this experiment, the size of the sample was 45. A power analysis was performed using equation (1) to statistically answer the question of whether this number of subjects was sufficient for this investigation.

$$n = \frac{\left(Z_{\partial/2} + Z_{\beta}\right)^2 \sigma^2}{\varepsilon^2}, \tag{1}$$

where $Z_{\partial/2}$ is the upper $(\partial/2)$th quantile of the standard normal distribution, Z_{β} is the upper (β)th quantile of the standard normal distribution, σ is the standard deviation of the normal distribution population, and ε is the difference between the true mean response of a test factor and a reference value, which can be given by $\varepsilon = \pm\delta\sigma$, the value of δ is between 0.25 and 0.5. Typically, a 10% level of significance is often used to represent a 90% confidence level in the unknown parameter. To balance the power and cost effectiveness, a power of 80% and a meaningful difference of 0.5 were employed in this study [25]. The findings revealed that the needed minimum sample size for this study was 25. This shows that the experimental design can provide persuasive answers to the questions raised in this study.

2.2. Apparatus. Our static cognitive experiment was conducted in a closed and quiet room at the Beijing University of Technology (see Figure 2). E-prime is an advanced graphic design environment, which is suitable for psychological and behavior-related experiments. It can automatically record response time in accordance with the actions of the participants. E-prime has been used in static cognitive experiments in many similar studies [24]. In this experiment, the drivers' visual cognition time for VMS was accurate within milliseconds.

A laptop was provided to run the E-prime software and record the participants' answers. The experimental equipment included a 42-inch liquid crystal display (LCD) to clearly display the images of the VMS. Paper and pens were also used to record experiment-related information. The premade graphical VMS was presented on the operating platform and then projected onto the high-definition (HD) display screen. During the experiment, the participants obtained VMS information by watching the HD display screen.

Considering the difference in visual cognition distance between our static experiment and a natural environment, this experiment defined the distance between drivers and the LCD depending on human factor engineering. We attempted to make the drivers' visual cognition in the experiment similar to actual road conditions to avoid systematic errors caused by the test environment and other factors. Equation (2) was applied to determine the visual cognition distance between drivers and VMS [26].

$$L = \frac{h}{\tan\theta}, \tag{2}$$

where L is the distance between the driver's line of sight and the LCD screen, h is the height of the driver's line of sight from the edge of the LCD screen, and θ is the angle between

Table 1: Basic information of subjects.

Gender	Number	Age		Driving experience		Professional driver	Amateur driver
		AVG	SD	AVG	SD		
Male	29	38.9	11.8	10.4	5.7	17	12
Female	16	33.1	9.6	7.4	5.6	6	10
Total	45	36.8	11.6	12.8	10.5	23	22

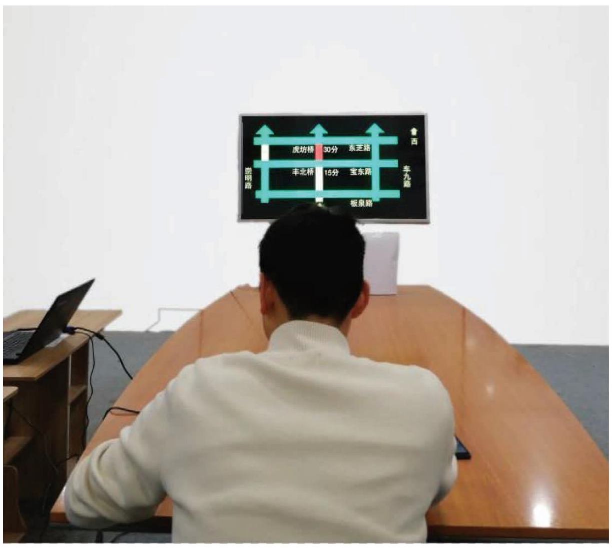

Figure 2: Environment of the static cognitive experiment.

the height of the driver's line of sight and the top edge of the LCD screen.

According to human factor engineering, drivers can clearly read displayed information when $\theta \leq 8^{\circ}$ [27]. In this experiment, it was determined by measurement that $h = 0.28$ m and $\theta = 8^{\circ}$; thus, $L = 2$ m (see Figure 3).

2.3. Scenarios. To determine the amount of information and elements of graphics VMS display through static cognitive experiments, we first conducted a subjective questionnaire on driver demand and preference for VMS information. A total of 424 valid questionnaires were obtained. The survey results are depicted in Figure 4. As illustrated in Figure 4(a), the upper limits of most drivers' preference for the number of roads to be displayed on the graphical VMS are 4, 5, and 6, accounting for 30.67%, 22.41%, and 20.05% of the total number of subjects, respectively. More than 95% of the drivers believed that the maximum number of roads displayed on VMS should be 6. According to Figure 4(b), driver preference for elements shown on VMS was varied. In addition to the basic elements, including road name, key node name, current vehicle position, and driving direction, time and distance information was also preferred by many drivers. For example, 304 drivers preferred distance information, accounting for 71.70% of the total drivers. Distance/time information refers to the distance/time from the vehicle's current position to the next key node or road.

We determined the range of the number of roads to be shown on graphical VMS to be 3–7 roads through a static cognitive experiment. A method of contrast experiment was conducted to test whether the distance and time information shown on graphical VMS was reasonable. The results of the questionnaire indicated that in addition to the basic elements, many drivers subjectively preferred VMS with distance or time information provided. Therefore, corresponding to the basic elements of the VMS, distance and time information was treated as auxiliary information in our study. The auxiliary information was only displayed in the experimental group. In this case, the influence of time and distance information was considered to be the same. Thus, the time or distance randomly appeared on the VMS for the experimental group. Ten VMS were designed and tested in our experiment. The experimental group contained five VMS with auxiliary information (the road number ranged from three to seven). Five VMSs without auxiliary information were classified as the control group.

Figure 5 depicts examples of VMS used in our experiment. Graphics on VMS were designed according to the following principles:

(a) Basic information including the vehicle's current position, driving direction, road names, and key road node names were presented in both the experimental and control groups. Experimental groups were also provided with distance or time information.

(b) Traffic conditions in road sections included three types: normal (shown in green), slow (shown in yellow), and congestion (shown in red). All colors appeared randomly on the VMS.

(c) As driver familiarity with traffic signs affects visual cognition time [21], the road and node names used in this study were unfamiliar and completely random to drivers.

(d) Assuming that drivers were aware of the traffic conditions of their nearest crossroad, node names and traffic conditions were displayed from the second crossroad onwards along the driving direction.

(e) Vertical and horizontal roads along with roadway names next to the roads on VMS are designed based on actual road scenarios, assuming drivers would have equal cognitive behaviors regarding the roads presented in the two directions.

2.4. Experimental Design and Procedures. Before conducting the static experiment, all participants completed a short questionnaire on their demographics and a questionnaire to ensure that they did not have any health issues that would affect the experimental data and were not under the influence of drugs, stimulating food, or alcohol.

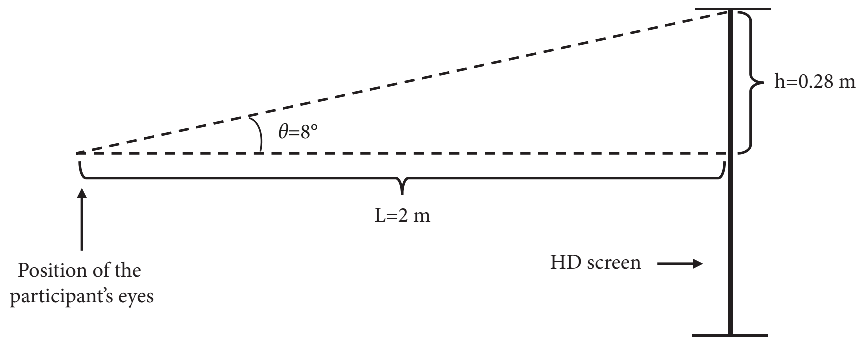

FIGURE 3: Illustration of the key parameters of the experimental condition.

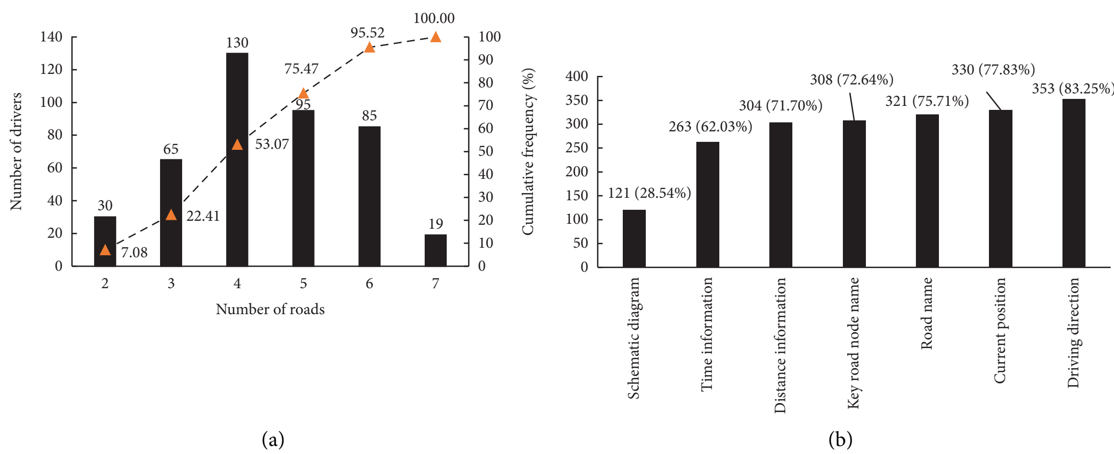

FIGURE 4: Statistical results of the subjective questionnaire survey. (a) Maximum number of roads accepted by drivers and (b) preference for elements showing on VMS.

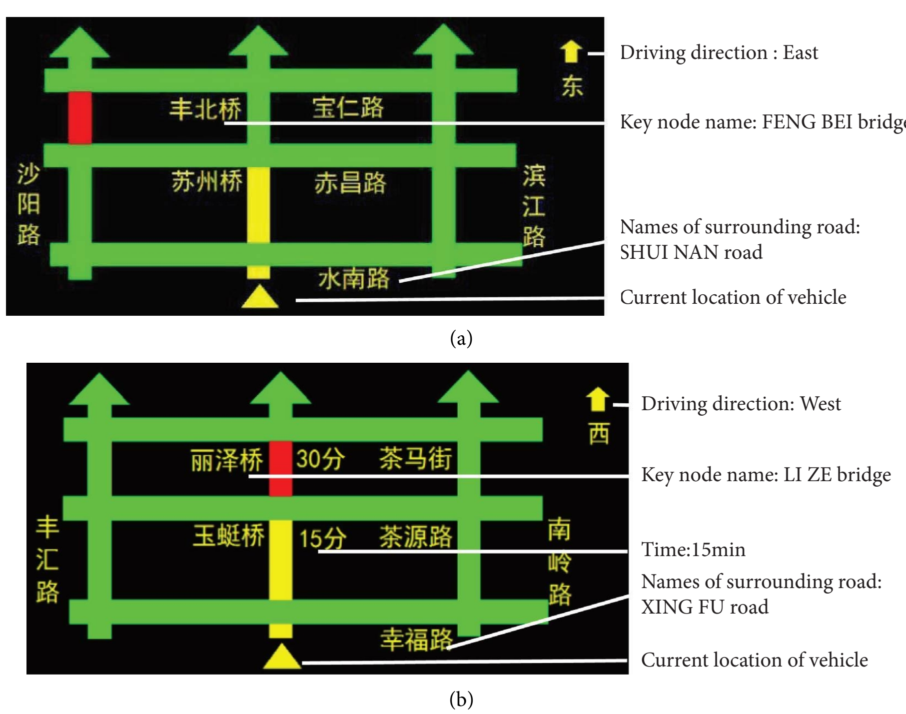

FIGURE 5: Control and experimental groups of VMSs (taking 6 roads as examples). (a) The control group (without auxiliary information). (b) Experimental group (with auxiliary information).

Previous studies have shown that practice affects driver performance in novel tests [28]. Thus, similar to the driving simulator experiment, we conducted a preliminary experiment before the formal test to familiarize the participants with the operation of the experimental apparatus and procedure.

Once the cognition experiment commenced, the VMS (e.g., image A) image was displayed on the screen. After they had observed and fully understood image A, participants pressed the "Z" key on the keyboard. The software recorded the time spent cognizing image A. Next, the screen displayed four images, labeled a, b, c, and d, among which only one was consistent with image A. Participants indicated which option was the same as image A and then pressed the "Z" key to continue. The next section was designed to examine whether participants read the VMS, to reflect the legibility of the VMS.

Another four options were displayed on the screen, among which only one option correctly reflected the information of image A. Participants chose an answer and informed the experimenter, who recorded the answer and instructed them to press the "Z" key to continue. This section studied the influences of different VMS information on drivers' degree of understanding.

Finally, the experimenter asked participants subjective questions orally. The first question concerned scoring image A for overall evaluation. The second question was designed to evaluate the acceptability of information provided by image A.

Through this process, every participant performed these experiment steps for each of the ten VMS and provided answers. Each participant took approximately 20–25 min to complete the static experiment. To reduce drivers' familiarity with the experimental contents, a random sequence of test scenes was generated for each participant. To avoid visual fatigue from viewing VMS, landscape images were randomly inserted to provide participants with short breaks and adjustments between normal tests.

2.5. Data Processing and Analysis

2.5.1. Data Preprocessing. Using E-prime software, visual cognition data for 45 participants were exported and preprocessed. Visual cognition data were logarithmically transformed and met the requirement of the homogeneity test ($p = 0.703$). According to Figure 6, the test results of the Q-Q graph indicated that the data were distributed on both sides of the diagonal line, which essentially verified the normal distribution of driver visual cognition data. Additionally, as the data sample was larger than 10, the original data were processed by the PauTa Criterion and the abnormal data were removed [19]. The PauTa criterion is a method to calculate the SD within a group to determine the error interval according to a certain probability. The specific steps are as follows:

(a) Testing whether the experimental data are the normal distribution or approximately normal distribution

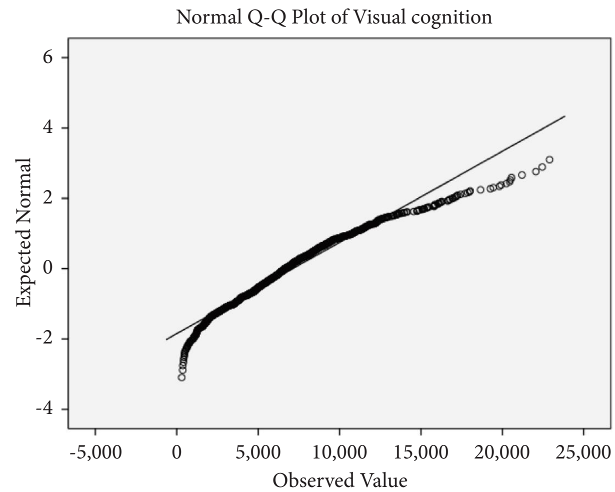

Figure 6: Driver's visual cognition data Q-Q graph.

(b) Calculating the standard deviation of the data sample

(c) Using $\mu + 3\sigma$ and $\mu - 3\sigma$ to eliminate abnormal data in the experiment

(d) Recalculating the deviation and standard deviation of the remaining experimental data after elimination, until the deviation is less than 3σ

After processing, data from 42 participants were used in the following analysis. The sample size selected in this experiment is larger than the minimum required sample size. In addition, to ensure the reasonableness of the sample size used in our current study, eight relative papers published in recent 5 years were referenced (see Table 2). So, a total of 42 participants in our current study would meet the minimum sample size requirements.

2.5.2. Analysis Indexes. In this study, a total of five static experimental-based indexes were used to assess the influences of different VMS information on driver visual cognition behavior to determine the information threshold of graphical VMS.

(1) *Visual cognition time (VCT).* VCT is the time taken by drivers to cognize VMS. Studies have reported that 90% of driving-related external information during driving was mainly obtained visually [37]. In addition, the longer cognize time might lead to a higher risk of accidents [38]. Thus, VCT is an important index for exploring the relationship between the amount of VMS information and driver visual cognition behavior. A lower VCT for VMS conserves time and attention for driving.

(2) *Visual cognition accuracy (VCA).* VCA represents the proportion of correct driver interpretation of VMS information. VCA was used to evaluate the legibility of the VMS. As the legibility of the VMS increased, the time for drivers to collect valid

Table 2: Typical examples of the sample size in previous studies.

Year	Sample size	Title	Author
2018	16	Representativity and univocity of traffic signs and their effect on trajectory movement in a driving-simulation task: regulatory signs	Vilchez [29]
2018	40	The effectiveness of eco-driving training for male professional and nonprofessional drivers	Wu et al. [30]
2019	24	Multivariate analysis of fuel consumption related to eco-driving: interaction of driving patterns and external factors	Lois et al. [31]
2019	23	A preliminary investigation into the impact of connected vehicle human-machine interface on driving behavior	Ahmed et al. [32]
2020	20	Assessment of the effectiveness of connected vehicle weather and work zone warnings in improving truck driver safety	Raddaoui et al. [33]
2020	35	Spatiotemporal characteristics of vehicle trajectories in a connected vehicle Environment—a case of an extra-long tunnel scenario	Chang et al. [34]
2021	32	Influence of the median opening length on driving behaviors in the crossover work zone—a driving simulation study	Difei et al. [35]
2022	45	Assessing the effect of long-automated driving operation, repeated take-over requests, and driver's characteristics on commercial motor vehicle drivers' driving behavior and reaction time in highly automated vehicles	Samani et al. [36]

information decreased. Thus, a reasonable VMS design should have a high VCA and a low VCT.

(3) *Comprehension accuracy (CA)*. CA reflects the proportion of drivers who understand exactly the information provided by VMS. A low CA indicates that the information provided by VMS is too complex or unreasonable. A higher CA helps prevent driver confusion regarding traffic conditions, driving directions, and other VMS information.

(4) *General assessment (GA)*. GA indicates the driver's subjective evaluation score for VMS design elements (1 = not good to 5 = very good), including the layout of text and graphics, information content, line thickness, appearance, visibility, and any other factors influencing driver cognition behavior.

(5) *Information acceptance (IA)*. IA reflects the subjective feelings of drivers for different numbers of roads and auxiliary information displayed on VMS (1 = not easy to accept to 5 = easy to accept). An excess of information on VMS makes assimilation in a short time difficult for drivers.

2.5.3. Analysis Method and Procedure. In this study, descriptive statistics, statistical hypothesis testing, and the TOPSIS model were sequentially applied to data analysis. First, the relationship between each evaluation index and the number of roads on VMS were to be analyzed by descriptive statistics. The influences of auxiliary information on drivers' VCT and the relationship between information volume and visual cognition behavior were explored through parametric and nonparametric tests depending on the variable type. To obtain the information volume threshold of VMS more accurately, the TOPSIS model was adopted to thoroughly evaluate the performance of VMS [39].

3. Results

3.1. Descriptive Statistics. After deleting the abnormal visual cognition data, a total of ten VMS tested by 42 participants were analyzed. Table 3 summarizes the AVG and SD of the five evaluation indexes. Figure 7 shows the trend of each indicator with the number of roads displayed in the simulated VMS increases.

3.2. Analysis of Evaluation Indexes

3.2.1. Visual Cognition Time. The average VCT of 42 drivers for the control and experimental groups was calculated, as depicted in Figure 6(a). It was observed that the VCT increased substantially with the increase in the number of roads in both groups. The VCT of the experimental group was higher than that of the control group for all numbers of roads. The difference gradually decreased with an increasing number of roads when the number of roads is less than or equal to 5. Thus, the VCTs of the drivers were almost positively correlated to the number of roads. The difference in cognitive time for VMS with and without auxiliary information was small when the number of roads increased to greater than five. The results show the influence of auxiliary information on drivers' visual cognitive behavior becomes weaker with the increasing number of roads.

As the VCT data satisfied the homogeneity test of variance, a two-way variance analysis (ANOVA) was applied to dissect the effects of auxiliary information and the number of roads on VCT. The results indicated that at the 95% confidence level, there was no significant difference in VCT ($F_{(1,400)} = 3.134$ and $p = 0.077$) with auxiliary information; however, the effect of the number of roads on VCT was apparent ($F_{(4,400)} = 10.654$ and $p < 0.001$). In addition, post-hoc multiple comparisons were used to compare differences

Table 3: Descriptive statistical results of drivers' visual cognition behavior.

The numbers of roads	Auxiliary information (with/without)	Visual cognition time (milliseconds)		Visual cognition accuracy (%)	Comprehensibility accuracy (%)	General assessment		Information acceptance	
		AVG	SD	AVG	AVG	AVG	SD	AVG	SD
3	Without	9012.76	4106.96	100.00	66.67	4.29	0.81	4.12	0.77
4	Without	11914.02	6122.68	100.00	69.05	4.19	0.86	4.12	0.89
5	Without	11649.98	5949.35	95.24	80.95	4.10	0.93	3.98	0.87
6	Without	16827.18	9273.63	97.62	61.90	3.74	1.06	3.55	1.06
7	Without	18902.88	13779.88	100.00	52.38	3.67	1.03	3.31	1.00
3	With	11239.76	5358.87	100.00	76.19	4.17	0.85	4.14	0.81
4	With	13540.21	6858.55	100.00	66.67	4.17	0.76	3.98	0.81
5	With	12509.71	5717.59	100.00	69.05	4.10	0.91	3.93	0.87
6	With	16899.31	9071.09	100.00	61.90	4.02	0.92	3.81	1.04
7	With	20222.60	11688.90	100.00	47.62	3.76	1.03	3.45	1.02

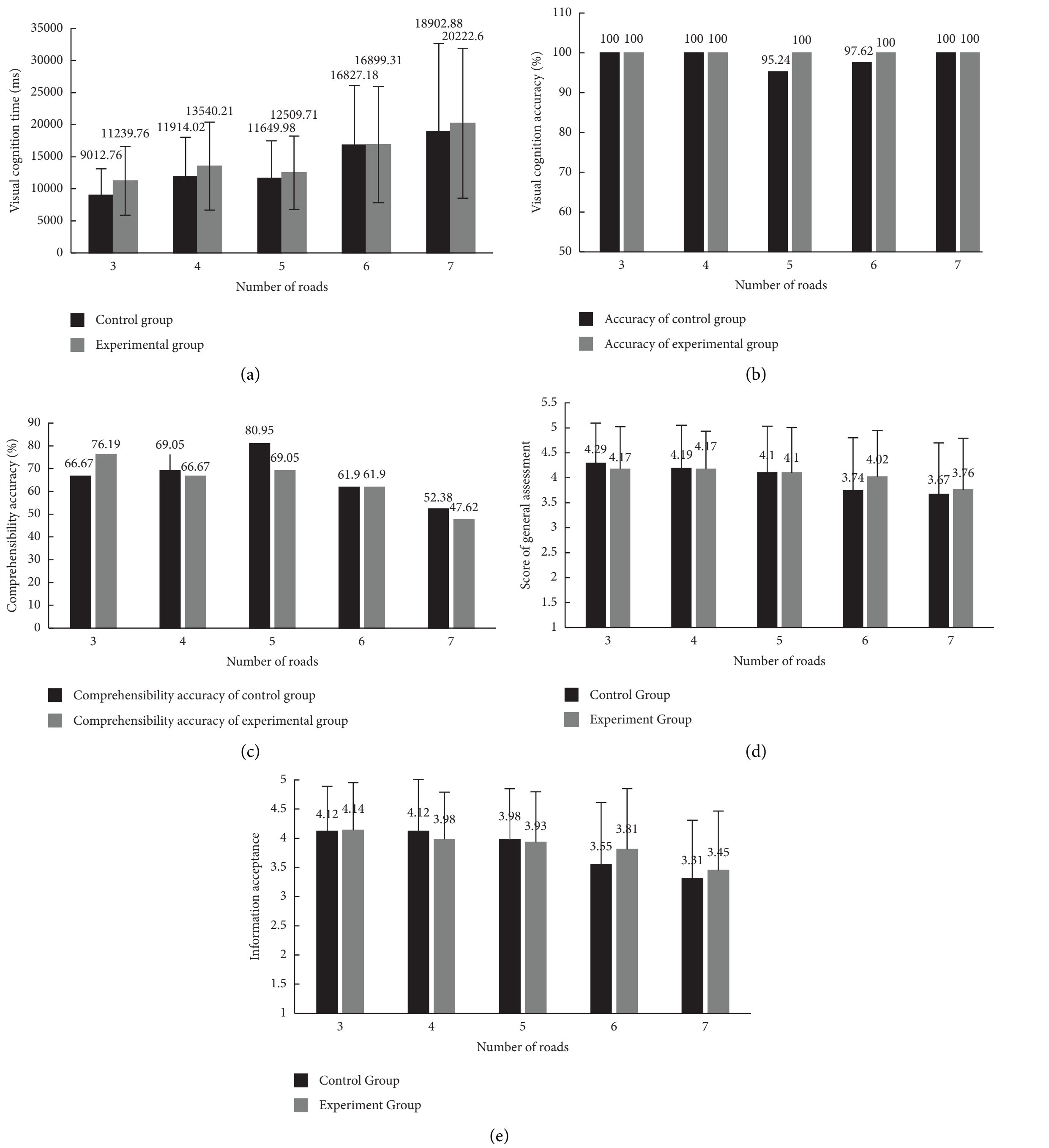

Figure 7: The trend of change for different indexes. (a) Visual cognition time. (b) Visual cognition accuracy. (c) Comprehensibility accuracy. (d) Score of general assessment. (e) Information acceptance.

in the number of roads, indicating significant differences between six roads and less than six roads ($p < 0.001$ for three roads, $p = 0.028$ for four roads, and $p = 0.006$ for five roads); the VCT for six and seven roads did not show a significant difference ($p = 0.201$). Thus, the impact of additional distance or time information on VCT was not obvious, particularly for VMS with more than five roads. However, an increase in the number of roads shown on VMS significantly affected the VCT.

3.2.2. Visual Cognition Accuracy. The legibility of VMS is represented by the driver's VCA. As depicted in Figure 6(b), the mean of VCA for both the control and experimental groups was high for different numbers of roads, increasing to 100% for the experimental group. For discontinuous independent variables, the Friedman nonparametric test was used for different analyses. The test results indicated that at the 95% confidence level, the VCA between the experimental and control groups was not significantly different ($\chi^2 = 3.000$

and $p = 0.083$). In addition, the VCA of the control group and the experimental group was not obviously different for different numbers of roads ($p > 0.05$ in all cases), indicating that all drivers could correctly identify VMS, and the legibility of VMS used in this study was satisfactory.

3.2.3. Comprehension Accuracy. CA represents whether participants understand the meaning of the information displayed on VMS. The driver CA for different VMS is depicted in Figure 6(c). The CA decreased with an increasing number of roads for both the experimental and control groups. The maximum CA value was reached when the number of roads was five. When the number of roads was three, the CA for the experimental group was higher than that for the control group. The CA of the experimental group was lower than that of the control group when the number of roads was greater than or equal to 4. The Friedman test results revealed that at the 95% confidence level, there was no remarkable difference in drivers' understanding of VMS between the experimental and control groups ($\chi^2 = 2.273$ and $p = 0.132$). The CA for the control group was obviously different with a change in the number of roads ($\chi^2 = 28.444$ and $p < 0.001$). According to the mean ranks of the Friedman test, five roads were optimal, with a value of 3.37. For the experimental group, the CA was also significantly different for different numbers of roads ($\chi^2 = 28.320$ and $p < 0.001$). The mean rank for five roads was the second highest, with a value of 3.13. To summarize, with an increase in VMS information, driver CA gradually decreases, i.e., too much information may hinder the understanding of VMS.

3.2.4. General Assessment. The drivers' GA scores for VMS with different numbers of roads are depicted in Figure 6(d). Particularly, when the number was greater than five, the GA for both the control and experimental groups was negatively related to the number of roads. The GA for the experimental group was higher than that for the control group when the number of roads was greater than five. The results of the two-way ANOVA at the 95% confidence level indicated that GA was not significantly different for VMS with and without auxiliary information ($F_{(1,414)} = 0.282$ and $p = 0.596$); however, the effect of the number of roads on GA was significant ($F_{(1,414)} = 4.623$ and $p = 0.001$). Three to five roads were classified in the same group without significant differences by post-hoc multiple comparisons ($p = 0.388$). Six and seven roads were classified into another group ($p = 0.241$). Overall, drivers exhibited a positive attitude toward VMS with appropriate information. The drivers' subjective feelings decreased if too much information was displayed.

3.2.5. Information Acceptance. Figure 6(e) depicts the drivers' IA score for VMS with different numbers of roads. With the increase in the number of roads, the IA for both the control and experimental groups decreased gradually. The IA of the experimental group was higher than that of the control group when the VMS displayed more than five roads. Similar to GA, drivers' IA was higher for VMS with distance or time information when the number of displayed roads was relatively large. The Friedman test results indicated that at the 95% confidence level, there was no remarkable difference in IA between the control and experimental groups ($\chi^2 = 3.125$ and $p = 0.077$). The IA for the experimental and control groups was significantly different for all numbers of roads ($p < 0.01$ in all cases). The mean rank decreased as the number of roads increased.

3.3. Comprehensive Evaluation Based on TOPSIS. TOPSIS is a common scientific method for multiobjective decision analysis. It evaluates the relative advantages and disadvantages of the evaluation object by calculating the difference between the evaluation object and the optimal objective. TOPSIS algorithm can make full use of original data, thus reducing information loss [40]. It also avoids the subjectivity of the data and can well portray the comprehensive influence of multiple impact indicators. So, it is an effective multi-criteria decision-making method that has been increasingly applied to traffic-related studies [19, 39]. To quantitatively evaluate the comprehensive effect of VMS with different numbers of roads on drivers' visual cognition behavior and to determine the threshold number of roads, the TOPSIS method was adopted.

First, all the indexes were evaluated to determine whether they varied in the same direction as the number of roads increased. Equation (3) was used to transform VCT into the same change trend as the other indexes.

$$X_{ij}' = \frac{1}{X_{ij}}, \tag{3}$$

where X_{ij} is the original data, X_{ij}' is the data after trend transformation, i is the number of roads displayed in the simulated VMS for experimental and control groups ($i = 1, 2, \ldots, 10$), and j is the evaluation index ($j = 1, 2, \ldots, 5$).

Second, normalized evaluation indexes were calculated using equation (4). The optimal and worst vectors of the evaluation results were determined. The optimal vector was $Z^+ = (0.458, 0.318, 0.388, 0.337,$ and $0.340)$, and the worst vector was $Z^- = (0.204, 0.303, 0.228, 0.288,$ and $0.272)$.

$$Z_{ij} = \frac{X_{ij}'}{\sqrt{\sum_{i=1}^{10} \left(X_{ij}'\right)^2}}, \tag{4}$$

where Z_{ij} is the normalized index.

Third, the weights of the five indexes were calculated based on the entropy weight method (see equations (5)–(9)), yielding 0.29, 0.11, 0.18, 0.22, and 0.19, respectively.

$$W_j = \frac{1 - H_i}{m - \sum_{i=1}^{m} H_i}, \tag{5}$$

$$H_i = -k \sum_{j=1}^{n} f_{ij} \ln f_{ij}, \tag{6}$$

$$f_{ij} = \frac{r_{ij}}{\sum_{j=1}^{n} r_{ij}}, \tag{7}$$

Table 4: Ranking results of different evaluation indexes and their optimal values.

No.	The number of roads	Group	D^+	D^-	C_i	Rank
1	3	Control	0.012	0.078	0.863	1
2	4	Control	0.034	0.048	0.585	4
3	5	Control	0.031	0.054	0.638	3
4	6	Control	0.066	0.018	0.212	8
5	7	Control	0.076	0.006	0.074	9
6	3	Experiment	0.027	0.056	0.675	2
7	4	Experiment	0.047	0.036	0.439	6
8	5	Experiment	0.039	0.043	0.524	5
9	6	Experiment	0.065	0.020	0.234	7
10	7	Experiment	0.081	0.003	0.038	10

$$k = \frac{1}{\ln n}, \tag{8}$$

$$r_{ij} = \frac{a_{ij} - \min\left|a_{ij}\right|}{\max\left|a_{ij}\right| - \min\left|a_{ij}\right|}, \tag{9}$$

where W_j is the weight of each index, H_i is the entropy of the i^{th} index, and it is assumed that when $f_{ij} = 0$, $f_{ij} \times \ln f_{ij} = 0$, f_{ij} is the proportion of standardized indicators at all levels, m is the number of evaluation indexes, n is the measurement level under each index, k is the Boltzmann constant, r_{ij} is the normalized result of the original indicator matrix, and a_{ij} is the unit vector of the normalized index.

The Euclidean distance of each index was calculated using equations (10) and (11).

$$D_i^+ = \sqrt{\sum_{j=1}^{5} \left[\left(a_{ij\max} - a_{ij}\right) \times W_j\right]^2}, \tag{10}$$

$$D_i^- = \sqrt{\sum_{j=1}^{5} \left[\left(a_{ij\min} - a_{ij}\right) \times W_j\right]^2}, \tag{11}$$

where $a_{ij\max}$ is the largest vector in the normalized vector, $a_{ij\min}$ is the smallest vector in the normalized vector, D_i^+ is the Euclidean distance of the optimal scheme of a certain scheme, and D_i^- is the Euclidean distance of the worst scheme of a certain scheme.

Finally, C_i was calculated using equation (12), and sorted according to C (see Table 4).

$$C_i = \frac{D^-}{D^- + D^+}, \tag{12}$$

where C_i is the degree of proximity to the optimal solutions under different design layouts.

The value range of the comprehensive evaluation score (C_i) was 0-1. A larger C_i indicates better visual cognition of VMS. Table 4 presents that with the increase in the amount of graphic information displayed on VMS, the comprehensive evaluation score gradually decreases. The control group had higher comprehensive scores than the experimental group for VMS with the same number of roads. When the number of roads was less than five, the C_i values of the experimental group and control group were greater than 0.5, and the comprehensive performance were above the medium level. However, C_i was lower ($C_i < 0.3$) when the number of roads was greater than five and considerably different from the C_i for five or fewer roads; the comprehensive performance was poor. The comprehensive evaluation scores for the control and experimental groups with five roads were better than that with four roads. Thus, the threshold of roads shown on VMS should be five to achieve good visual cognition.

4. Verification

The dynamic simulation experiment was conducted based on the static cognitive experiment results for verification and optimization. To further determine the threshold value of the number of roads, VMSs with four, five, and six roads were selected for further investigation in this experiment. The layout and design of the graphical VMSs were consistent with those used in the static cognitive experiment. This experiment simulated a two-way, four-lane highway with a speed limit of 60 km/h, and the weather and roadway conditions were sunny and dry.

A total of 32 drivers—20 male and 12 female—aged 23–59 years (M = 39.4, SD = 12) and having at least one year's driving experience, were re-recruited. Because the cost of the driving simulation experiment was higher than the static cognition experiment, the number of participants was usually less than the static cognition experiment. The dynamic simulation experiment was performed in a quiet laboratory at the Beijing University of Technology. Experimental instrumentation included a dynamic driving simulation system, a computer controller, driver performance equipment, and a liquid crystal screen (see Figure 8). The current laws and guidelines in China were always followed during the whole experimental procedure.

To reduce drivers' familiarity with the content of the experiment, the sequence of experimental scenes for each participant was generated randomly. The averages and standard deviations of the four evaluation indices were calculated based on the data collected from the 32 participants, and the results are shown in Figure 9.

The averages and standard deviations of the four evaluation indices were calculated based on the data collected

Figure 8: Dynamic simulation experiment environment.

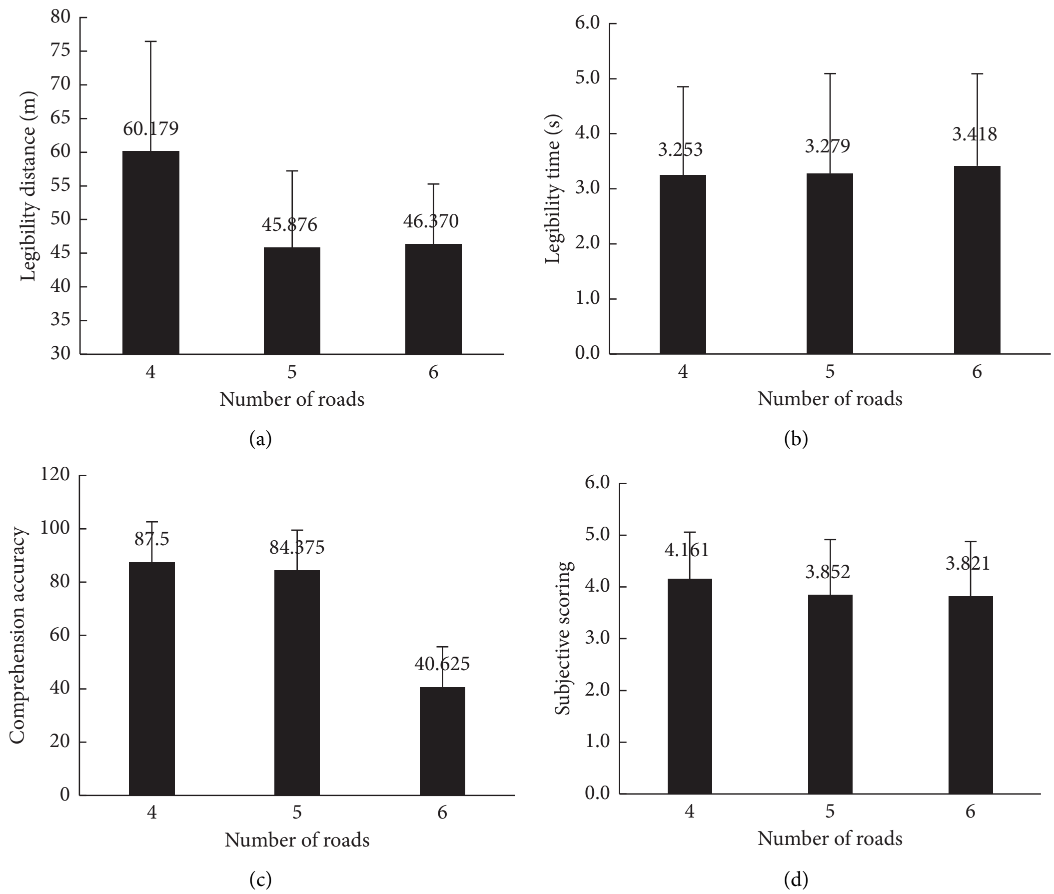

Figure 9: Statistical results of dependent variables.

from the 32 participants, and the results are shown in Figure 7. These four indices are defined as follows:

(i) Legibility distance refers to the distance between the driver's legibility point and the VMS position

(ii) Legibility time was considered as the time taken by the driver to observe the information on the VMS and confirm the display of the information

(iii) Comprehension accuracy is the percentage of participants who correctly identify VMS information

(iv) Subjective scoring is the overall subjective evaluation of the VMS displayed by each participant. The available ratings ranged from 1 to 5.

Figure 9 presents the changing trend of different indicators with the increase in the number of roads, only the legibility time was positively correlated with the number of roads. Moreover, when the number of roads increases to six, only about 40 percent of drivers have access to layout information correctly. In summary, the results of introducing speed conditions into the experiment were consistent with the conclusions of the static cognitive experiment. Therefore, the threshold of roads on the graphical VMS can be eventually determined as five.

5. Discussion

Previous studies have played a positive role in standardizing the VMS layout attributes and optimizing the information contents [9, 10], but it is still not much clear about the threshold value of VMS layout information. The information overload is one of the main problems for VMS in practice. Our current study provides a scientific and cost-effective experimental test way to get the threshold value for the number of roads displayed on VMS. First, the possible candidates were obtained by subjective questionnaire from the perspective of driver demand. Then, based on an indoor static cognitive experiment, the objective and subjective evaluation data of drivers for the number of roads displayed on VMS was obtained in this study. The relationship between the number of roads displayed and the cognitive demand of drivers was explored, and the threshold value for the number of roads displayed on VMS was preliminarily determined. Finally, the results of the static cognition experiment were verified and refined by conducting a dynamic simulation experiment. Based on the three-stage study process, the value of the information volume threshold was gradually verified and optimized, thus increasing the credibility of the study results. Meanwhile, the cost of the experiment was extremely reduced. Although VMS formats and drivers' characteristics might be different, this research method could be promoted and applied widely.

According to the results of the questionnaire, 75.47% of drivers thought that the number of roads shown on VMS should be below or equal to five. Based on the analysis of the static cognitive experiment, the drivers' VCTs generally increased with increasing information on VMS. There were no significant differences in VCTs between five and less than five roads. However, the VCT increased significantly with more than five roads. Depending on the analysis results by TOPSIS, the number of five roads is the critical point for the comprehensive evaluation score. The score was above the medium level when the number of roads on VMS was less than five, while it was relatively low with more than five roads. Therefore, the upper limit for the number of roads shown on the graphical VMS should be five to ensure good visual cognition. The current findings provided supplements for the existing standards of VMSs [9, 10] and thus were useful for designing and setting graphical VMS in practice.

The results of the questionnaire indicated that drivers' preferences for design elements displayed on VMS were various. In addition to the basic elements (i.e., driving direction, current position, and road name), many drivers subjectively preferred VMS with distance or time information provided between the current position and the next location. Generally, it is beneficial to eliminate drivers' uncertainty regarding road conditions and therefore plays a positive role in road networks by providing drivers with distance or time information [41, 42]. According to the result of TOPSIS, for VMS with the same number of roads, the comprehensive score of the experimental group was lower than that of the control group. However, for each evaluation index, the differences between the experimental and control group were not significant. So, the auxiliary information affects the drivers' visual cognition behavior to some extent, but the influence is weak. As for the study guided by Chen et al. [43], the average speed was positively affected in the long run when the driving time was displayed on VMS. Thus, it was recommended to provide drivers with time or distance information on graphical VMS. The current study results are consistent with the results of previous studies [41, 42].

In addition, previous research results indicated that the time for drivers to cognize traffic signs was less than 4 s [20]. Moreover, looking away from the road for a long time increases the risk of accidents [44]. However, the average VCT in our study was higher than that in a realistic driving environment. The explanation for the higher VCT would be two aspects. First, since the static cognitive experiments did not address the effects of vehicle operating speed, traffic volume, external environment, and other factors on driver visual recognition characteristics, resulting in higher VCT than the real values [17]. Namely, the fixation time of drivers used for observing the external road and traffic information during driving was reduced. Second, participants might feel less risky in static experiments subconsciously, which allows them more time to observe information on VMS.

In the dynamic simulation experiment, participants were requested to read the information displayed on a VMS while driving simulated vehicles according to their actual driving habits in a realistic environment. Unlike the static experiment, speed and distance are the main factors affecting information obtained from the VMS [45]. The greater speed would lead to a shorter time that drivers spent observing the VMS. In addition, if the distance between the driver's legibility point and the VMS position was longer, drivers might spend more time observing the VMS [14]. In the current study, both legibility distance and legibility time in dynamic simulation experiments were used to verify the study results from the static experiment. Although the VCT in our study was not sufficiently scientific to represent the value in an actual driving environment, it is sufficient to explore the changing trend of VCT among VMSs with different information volumes.

Some limitations should be addressed in future studies. The influence factors such as speed, traffic volume, and external environment were not considered in the static cognitive experiment, the visual recognition feature data might be different from the actual value. Although the experimental results were verified by dynamic simulation experiments, it is necessary to further test the study results by a large-sample, real-vehicle experiment (e.g., with the help of vehicle trajectory monitoring data) in the future. The study results were obtained from the perspective of driver visual cognition behavior, the influence of VMS on driving behavior, and vehicle running status could be explored in combination with dynamic experiments to further optimize the experimental results. The current experiment focused on the typical type of VMSs in Beijing, the comparisons with foreign VMSs or other forms of VMS were needed to improve the applicability and robustness of the results. Forty-two drivers participated in the experiment; according to the requirement of minimum sample size and experience of previous studies, large-scale field tests (in the form of Internet approaches) were necessary to further clarify the information volume threshold for graphical VMS.

6. Conclusions

In this study, a static cognitive experiment based on a subjective questionnaire was jointly conducted to analyze the influences of graphical VMS with different information volumes on the visual cognition characteristics of drivers and to explore a suitable number of roads to be displayed on graphical VMS. A subjective questionnaire was used to obtain the drivers' assessments and preferences for graphical VMS, and a static cognitive experiment was designed based on its findings. A total of 42 participants were recruited for the static cognitive experiment. Five feature indexes, including VCT, VCA, CA, GA, and IA, were used to represent the cognition characteristics influenced by VMS. The TOPSIS model was used to comprehensively evaluate the performance of VMS with the different numbers of roads. Finally, the threshold for the number of roads was verified and refined by conducting a dynamic simulation experiment, increasing the credibility of this study.

Our study results indicated that drivers not only had high subjective preferences for basic design elements (driving direction, current position, and road name) displayed on graphical VMS but also showed a higher preference for auxiliary elements (distance or time information). A subjective survey demonstrated that the maximum amount of information generally acceptable for drivers was five or fewer roads. The drivers' visual cognition time increased and other companion indexes (VCA and CA) generally worsened with an increase in information volume. Using five roads as the threshold, the comprehensive score obtained by TOPSIS was high when the number of roads was less than five; the score decreased when the number of roads exceeded five. Therefore, we suggest that the maximum number of roads shown on the graphical VMS should be five. The result of the dynamic simulation experiment was consistent with the conclusion of the static cognitive experiment. Moreover, the distance or time information from the current position to the next key node or road should also be provided to the drivers through VMS. The current study results provide a foundation for more consistent and reasonable design standards and usage specifications for graphical VMS on highways in China to improve their effectiveness.

Data Availability

All data and models generated or used during the study appear in the submitted article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

This paper/work was supported by the Opening Fund of the Key Laboratory of Transportation Industry of Automotive Transportation Safety Enhancement Technology (Chang'an University), PRC (300102225065). This work was also supported by the Beijing Municipal Commission of Transport and the Beijing Traffic Engineering Association.

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