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Research Article

Research on the Relationship between Dynamic Message Sign Control Strategies and Driving Safety in Freeway Work Zones

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Several studies have researched the effect of dynamic message signs (DMSs) on the driving safety in work zones. However, only a few studies have examined the design of DMS control strategies in work zones. The purpose of this study is to investigate the effects of DMS control strategies on driving decisions and behaviors and to improve the driving safety in work zones by changing the content and placement of DMSs. In this study, five control strategies are proposed by combining five DMSs with different contents ("change lane" versus "go straight"). A total of 32 participants participated in this study. Each participant drove in five scenarios in a high-fidelity driving simulator corresponding to strategies 1-5. The results show that the control strategies have a significant effect on drivers' decisions and behavior (e.g., the driving speed, acceleration, and lateral placement). All strategies reduce the drivers' speeds and improve their control stability and compliance. After conducting analytic hierarchy process (AHP) analysis, strategy 2 was removed because the approaching speed exceeded the speed limit. The weight vectors of strategies 1, 3, 4, and 5 under free-flow traffic and traffic jam conditions are $\Upsilon_{\text{free-flow traffic}} = [0.25, 0.28, 0.17, 0.23]$ and $\Upsilon_{\text{traffic jam}} = [0.17, 0.28, 0.2, 0.3]$, respectively. These results show that strategy 4 is not suitable for free-flow traffic in work zones, while strategies 5 and 3 are suitable for traffic jams in work zones. Strategy 3 is suitable for both free-flow traffic and traffic jams. The first occurrence of a decision sign that contains lane change content is key to the driver's decision; in addition, the position of signage with such information should gradually be moved closer to work zones with increasing traffic flow.

1. Introduction

Traffic crashes are prevalent in work zones. According to a recent Crash Report on Road Safety in China [1], crashes on freeways accounted for 3.14% of all transportation-related occupational fatalities, amounting to a total of 1,000 fatalities in work zones in 2016; moreover, the death rate among work zones in China is 3 times greater than that in any other area. This higher number of fatalities reveals that the presence of a work zone generally impacts both the mobility and the safety of road users. Therefore, minimizing the adverse impacts associated with work zones has become a priority for road agencies [2].

Drivers are guided through a work zone by traffic control devices, including arrow panels and driving advice. Accordingly, enhancing the effects of traffic control devices on traffic safety continues to constitute a primary emphasis of work zone research. With the continuous development of technology, devices are not restricted to one-way communication from signs to drivers subject to individuals' safety awareness [3, 4]; as an alternative, two-way communication between drivers and an infrastructure is achievable through wireless communication networks. As a consequence, workers, vehicles, and infrastructures are more visible to each other, allowing workers and motorists to observe the traffic situations around them in a timely manner [5]. However, although such innovations are attractive, they remain in their infancy; in this stage, an effective control strategy for traffic control devices is required. However, such effective strategies have not been studied systematically [6].

Dynamic message signs (DMSs) have been shown to effectively influence driver behavior. DMSs have been widely used for traffic control in work zones in many countries (e.g., [7, 8]; Hassan et al., 2012; [9]). However, for DMSs to effectively influence the speed and compliance of drivers in work zones, drivers must be able to comprehend the messages of DMSs and obey the corresponding speed limits and control advice. Accordingly, the current study investigates the application of DMSs toward improving the overall driving safety and stability within work zones with the aim of determining the impacts of various DMS control strategies on drivers' decisions and behaviors in work zones. Then, the applicability of each strategy is analyzed, and appropriate DMS control strategies for different traffic flow situations are explored. The results of this study, which can be applied to work zones depending on the workers' requirements, reveal that drivers can be influenced more effectively if the DMS content is in accordance with current traffic conditions and if DMSs are repeated in front of work zones. Each of these hypotheses was tested using a high-fidelity driving simulator.

2. Literature Review

Many studies have focused on work zone safety (e.g., [10, 11]). A variety of interventions and standards, including those aimed at worker education [12], raising public awareness [13], increasing the presence of law enforcement [14], enhancing infrastructure and signage [15], and connecting vehicles to smart communication [16, 17], have been suggested to improve the safety and stability in work zones. In 2009, the Federal Highway Administration published the Manual on Uniform Traffic Control Devices (MUTCD) [18]. Part 6 of the MUTCD, which defines the standards used nationwide by road managers to install and maintain work zone traffic control devices, details the standard practices for work zone traffic controls and the color, font, and distance of traffic signs. However, although the MUTCD established rules for work zones, safety throughout work zones remains a concern. Subsequently, the Highway Safety Manual (HSM) was published in 2010, thereby providing a framework for road agencies to estimate the safety performance of various types of road facilities [19]. Moreover, the HSM provides methods for estimating the effects of work zones on limited-access facilities. More recently, the Operation Regulations for Highway Maintenance and Safety in China [20] was published in 2015 and defined the standards for work zone signs that outline their basic design factors, including their color, font, and distance; however, these standards do not adequately address their corresponding control strategies, including changes in the DMS content and the positions of DMSs in work zones.

According to the MUTCD, dynamic message signage represents only one form of intervention that has been used to effectively provide information regarding various road conditions and associated hazards [18]. DMSs can improve traffic safety considerably [21]. Furthermore, according to Dudek [7], DMSs increase the reading times of drivers. Mahmudur (2017) also concluded that DMSs can cause 7% of all drivers to decrease their driving speed. The limits of driver perception have always guided the design of specific DMSs. Additionally, many researchers have conducted research on numerous other aspects of DMSs, such as limits on the number of words, the font color, and the amount of information in a DMS (e.g., [22]). Other studies have demonstrated that short, direct messages are best for DMS communication (Mattox et al., 2007). Moreover, DMS control strategies affect the behavior of drivers in advance through compliance with speed reductions. For example, Strawderman et al. [9] investigated the impacts of DMS control strategies and sign placement on the behaviors of drivers approaching work zones by testing four DMS strategies and three placement distances (1,000, 1,500, and 2,000 feet) using a driving simulator; the results indicated that the resulting reduction in the driving speed was significantly impacted by the strategy employed. However, recent studies have also explored the misapplications of DMSs in work zones and revealed that DMSs can often contribute to driver confusion and anxiety regarding their appropriate path. In addition, Messina et al. [23] found that text messages are always present on a DMS, but graphic messages are more effective in terms of the corresponding response time and accuracy. Furthermore, Ullman (2015) found that the control strategies utilized in work zones are not standardized, thereby restricting the effects of DMSs.

Appropriate DMS control strategies can certainly enhance the safety in work zones. However, while some researchers have explored the effectiveness of DMSs, few investigations have been performed on combinations of control strategies. Consequently, the spacing, positioning and control modes of DMSs have not been thoroughly studied, principally because DMS experiments in work zones might cause traffic accidents, and thus, the experimental data are influenced by field restrictions. It follows that, for such research, a driving simulator offers multiple advantages, including (a) an environment with flexible experiment conditions, (b) an ability to provide crash-prone scenarios that are often unsafe to perform in real-life situations, and (c) an economical approach in addition to (d) less time needed to expose participants to a wide variety of situations and (e) convenience for objectively measuring driving performance. Moreover, a driving simulator can be used as a test platform for analyzing the effect of a particular control strategy. Therefore, this study uses a simulation driving system to investigate reasonable DMS control strategies for improving the driving safety and stability in work zones.

Most previous studies analyzed the layout of DMSs in the work zone, but the analysis of strategies of DMSs was limited. It has also explored the misapplications of DMSs in work zones and revealed that DMSs can often contribute to driver confusion and anxiety regarding their appropriate path. The purpose of this study is to investigate the effects of DMS control strategies on driving decisions and behaviors and to improve the driving safety in work zones by changing the content and placement of DMSs. Five strategies are designed based on changing the content and locations of DMSs, and appropriate DMS control strategies are explored for different traffic flow situations. This study is different from previous investigations insomuch that the strategies examined herein are far more precise and detailed. In summary, the results of this study can be used in work zones depending on the workers' requirements.

Table 1: Demographics summary.

Demographic Variables	Mean (SD) Statistics or Percentages	
	Male Participants	Female Participants
Age (years)	37.5 (13.1)	25 (12.97)
Age of license (years)	11.5 (8.21)	8.93 (6.97)
Average driving mileage (per year/km)	18524 (3548.22)	9584 (5514.21)
Average proportion of driving on:		
Rural roads	34%	22.75%
Urban roads	58.24%	72.55%
Freeway	7.76%	4.7%

3. Methodology

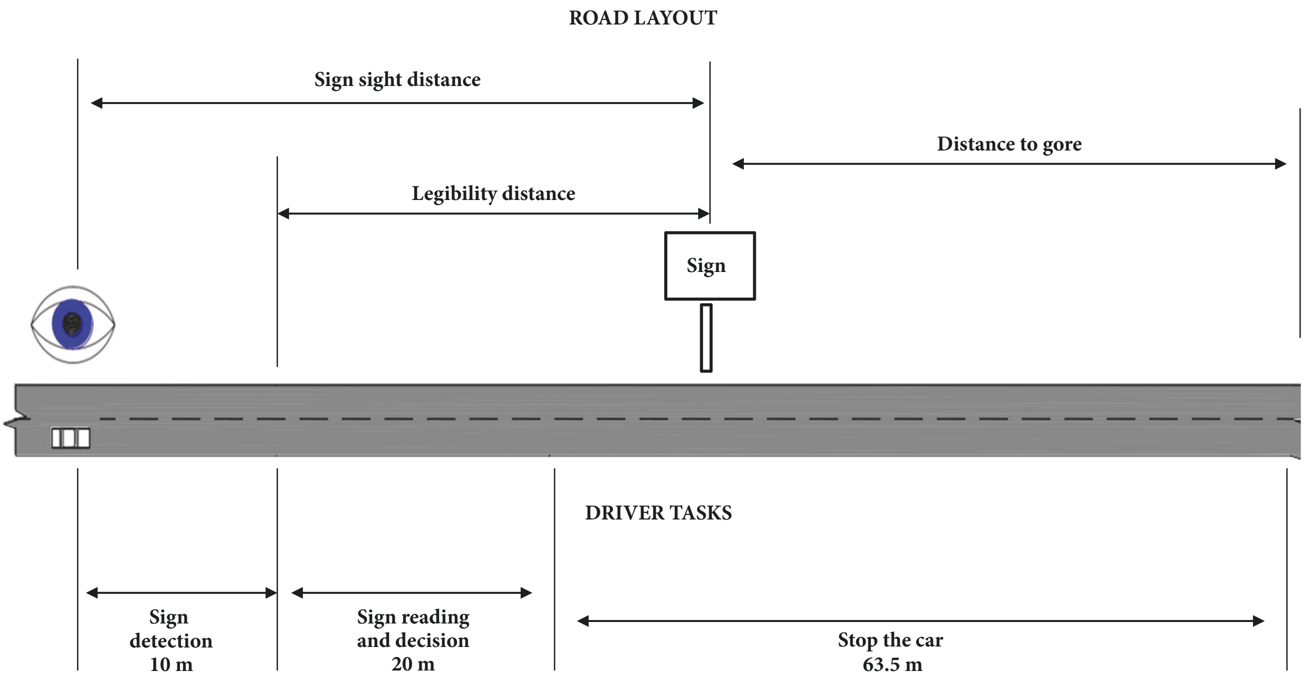
3.1. Participants. A total of 32 healthy participants, including 25 males and 7 females with a mean (M) age of 35 years with a standard deviation (SD) of 11.88 years, were recruited from universities and social organizations to participate in the experiment. The participants were required to have at least 20/20 (normal or corrected, self-reported) vision and to have no hearing problems (self-reported). A summary of the demographics of the participants is shown in Table 1. The participants were also required to have had a driver's license for a minimum of 3 years (license age: M = 10 years, SD = 7.94). All participants provided written informed consent before joining the experiment; drivers could not participate in the training until providing informed consent. After completing the driving experiment, each participant was offered 200 Chinese yuan (CNY) in cash as a reward.

In brief, a homogeneous sample of subjects was selected to minimize any biases attributable to heterogeneity within the sample [24]. Meanwhile, according to the central limit theorem, if a sum of random variables is normally distributed, a large sample size obtained from those variables also fits a normal distribution. For example, Ben-Bassat and Shinar [25] used 22 participants to study the effects of the shoulder width, the presence of a guardrail and the roadway geometry on driving behaviors. Similarly, research was also conducted on the influence of the roadside infrastructure on vehicle operation with 22 participants [26], and another study focused on the safety effects of enhanced road markings with 25 participants [27]. Moreover, the ages, age structure, and gender compositions of the participants were selected based on the characteristics of drivers who use the Chinese freeway system.

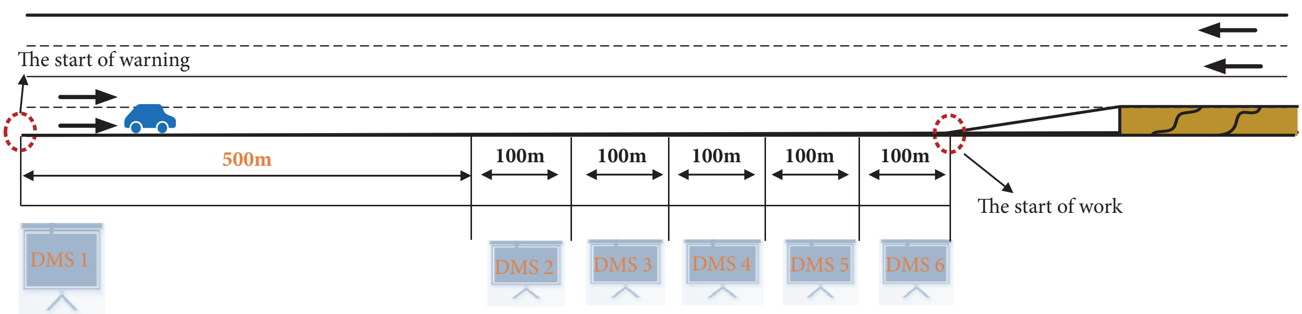
3.2. Apparatus. The fixed-base driving simulator located in the Key Laboratory of Traffic Engineering at the Beijing University of Technology consists of a real car, computers, computer-generated images, and audio equipment (see Figure 1). The road scenario was projected onto three large screens, thereby providing a 130-degree field of view. The resolution of each screen in the driving simulator was 1920 × 1080. The simulator recorded operating data (e.g., the braking force, acceleration, speed, lateral placement, lane numbers, and turning angle of the steering wheel) 30 times per second. Furthermore, an application programming interface (API) that allowed the users to design driving tasks according to their needs was adopted in the simulator. In addition, the driving scenarios were modified by using the API to add animated workers, signs, and other work zone elements.

Figure 1: Fixed-base driving simulator at the Beijing University of Technology.

3.3. Control Strategy. Two DMS design strategies are expected to effectively influence the behaviors of drivers: (a) repeatedly placing DMSs in front of work zones and (b) ensuring that the DMS content is in accordance with current traffic conditions. The aim of the DMSs in this study is to guide drivers toward making the correct decision for navigating through the work zone. DMS repetition is typically defined by two elements: the range of the repetition area and the frequency. In China, the warning area extends 1,000 m upstream of a work zone [20], and a warning sign with the text "ROAD WORK AHEAD" is always placed at this distance as the first temporary traffic control (TTC) sign. However, in consideration of vehicle speed profiles, this control strategy is more effective when the DMS is placed 500 m upstream of the work zone in China. After we study the several papers about the DMSs warning, the result of DMSs distance design was limit and confuse. So we choose the 500 m as the test design for analyzing the effectiveness of DMSs. Once a driver reads a sign, he or she must have the time to cognitively process the information, decide whether to maneuver, and execute the maneuver. Figure 2(a) illustrates these steps. In a preliminary experiment with five participants, the mean sign detection distance was 10 m, and the reading and decision-making distance was 20 m. The freeway speed limits in China range from 60 to 120 km/h, and the human reaction time is 0.1-0.4 s. Therefore,



(a) Steps in which a driver reads a traffic sign



	Content of TTC (DMS 1)	DMS 2	DMS 3	DMS 4	DMS 5	DMS 6
Control strategy 1	ROAD WORK AHEAD	Change Lane	Change Lane	Change Lane	Change Lane	Change Lane
Control strategy 2	ROAD WORK AHEAD	Go Straight	Change Lane	Change Lane	Change Lane	Change Lane
Control strategy 3	ROAD WORK AHEAD	Go Straight	Go Straight	Change Lane	Change Lane	Change Lane
Control strategy 4	ROAD WORK AHEAD	Go Straight	GoStraight	Go Straight	Change Lane	Change Lane
Control strategy 5	ROAD WORK AHEAD	Go Straight	Go Straight	Go Straight	Go Straight	Change Lane

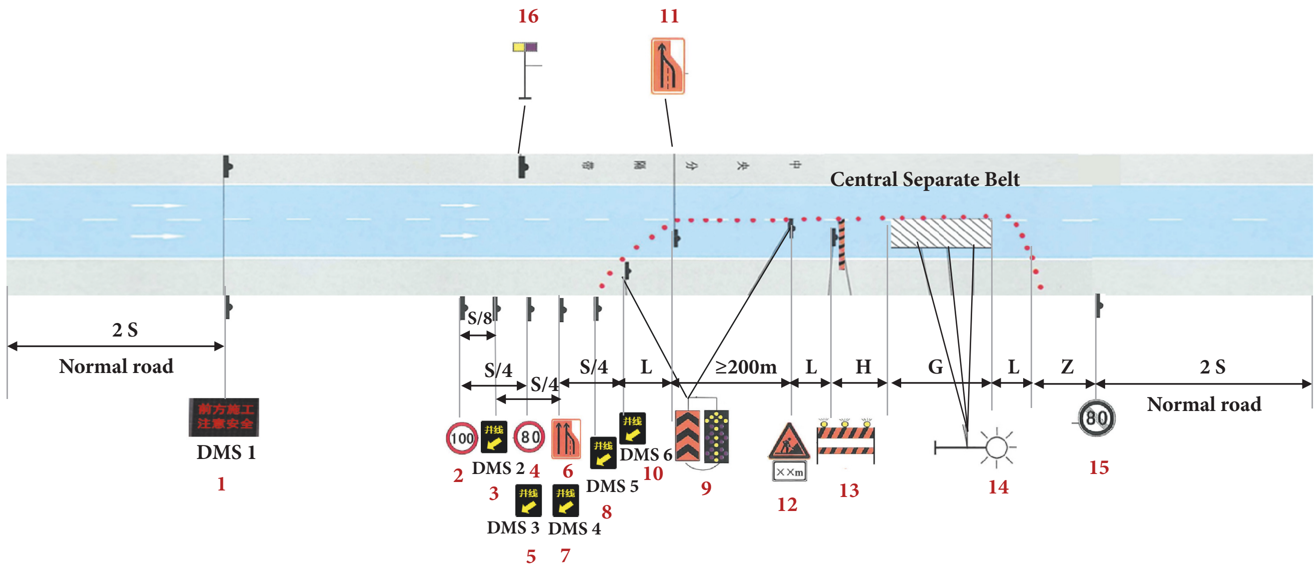
(b) Layout of the control strategies

Figure 2: Details of the DMS control strategies.

the maximum impact range of a DMS is 117 m, which can be calculated by (1) [28, 29]. Hence, five DMSs are placed within a distance of 500 m upstream from the work zone, and the interval between each DMS is 100 m. Furthermore, drivers have two choices when driving near a work zone: "change lanes" or "go straight". The DMS content is designed based on these choices, and the control strategies that meet the above requirements are presented in Figure 2(b).

$$D_{\mathrm{DMS}} = \frac{V^2 - Vo^2}{254\,(f + i + \omega)} + Vo * T_{reaction} + D_{sign\ detection} + D_{sign\ reading} \quad (1)$$

As written in (1), the impact range of each DMS (D_{DMS}) is calculated by the safety speed (V), the current speed (Vo), the drivers' reaction time ($T_{reaction}$), the distance a driver requires



Note:

S: The length of advance warning area (1000 m)

L: The length of transition area (50 m)

H: The length of buffer area (100 m)

G: The length of work activity area (1000 m)

Z: The length of termination area (100 m)

Figure 3: Standard layout and longitudinal cross-sectional structures of a work zone featuring the closure of the right lane.

to detect a sign ($D_{sign\ detection}$), the distance for drivers to read a sign ($D_{sign\ reading}$), the correction factor (f), the slope (i), and the friction coefficient (ϖ). The equation was built based on equation of braking distance, in the previous study which analysis the effective of DMS in the work zone [30], typically, V = 0 km/h, Vo = 100 km/h, f = 0.01, i = 0, ϖ = 0.6, $T_{reaction}$ = 1 s, $D_{\text{sign detection}}$ = 10 m, and $D_{\text{sign reading}}$ = 15 m. Therefore, the impact range of each DMS is 117 m, and thus, an interval of 100 m is chosen between each DMS.

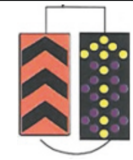
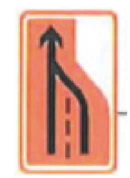
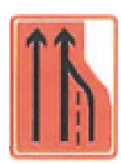
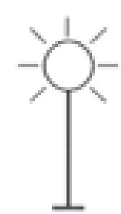
3.4. Driving Scenarios and Study Procedure. Work zones featuring the closure of the right lane are typical on the freeway [20]. Therefore, an experiment was designed with 1 (right-lane closure) × 5 (DMS control strategies 1, 2, 3, 4, and 5) scenarios. All scenarios were set on a two-way, four-lane freeway with a cross-sectional width of 26.3 m (lane width = 3.75 m, median (green belt) width = 0.8 m, and shoulder width = 1.50 m) and speed limits of 60-120 km/h under normal road conditions and 80 km/h in the work zone. Moreover, the Operation Regulations for Highway Maintenance and Safety provide detailed provisions for work zones on two-way, four-lane freeways, including standards for the work zone length and the deployment positions of different facilities (e.g., work zone starting signs, speed limit signs, guardrails, and reduced speed limit signs). A work zone usually includes a warning space, an upstream transition space, an upstream buffer space, a workspace, a downstream transition space, and a downstream buffer space (see Figure 3). Combined with the installation locations of signs and DMSs in work zones based on established standards [20], each scenario was 7 km long. The freeways were simulated in the daytime to eliminate the interference of confounding factors on the experimental data, and no other vehicles were present along the freeway.

Each scenario included an introductory drive segment prior to encountering work zone signage. A DMS with the text “WORK ZONE AHEAD” was located at the beginning of the warning area; the DMS was 8 m high, and the display panel material was a light-emitting diode (LED) with an area of 24 m^2 (4 × 6 m). DMSs 2 through 6 were each 2 m high with an area of 1 m^2 (1 × 1 m), and the explanations of these signs are shown in Table 2.

The procedure of this study included two parts.

(1) Predriving Practice. All participants were given the following instructions before driving on the simulator: “You are about to participate in a driving experiment on the simulator. During driving, please drive the way you normally do, but obey the traffic laws.” Participants were screened using questionnaires to determine their susceptibility to motion sickness or simulator sickness. Their initial responses were logged as a baseline for comparison throughout the experiment to check for any adverse reactions to the simulator. Following the questionnaires, the participants performed predriving practice for approximately 3-5 minutes. The main purpose of this practice was to minimize the impact of a participant’s unfamiliarity with the driving simulator and to allow each participant to become familiar with the simulator’s steering and braking dynamics in a potential scenario.

Table 2: Names and styles of the signs in work zones.

Item	Name	Style	Item	Name	Style
1∗	Warning sign (DMS 1)	 work zone ahead	9	Guide sign	 or
2	Speed limit sign		10∗	Control DMS (DMS 6)	 Change lane
3∗	Control DMS (DMS 2)	 Change lane	11	Working distance sign	
4	Speed limit sign		12	Lane reduction sign	
5∗	Control DMS (DMS 3)	 Change lane	13	A road fence with a warning lamp	
6	Lane reduction sign		14	Lighting facilities	
7∗	Control DMS (DMS 4)	 Change lane	15	Reduce speed limit sign	
8∗	Control DMS (DMS 5)	 Change lane	16	Warning flashing light	

∗: sign is designed based on the need of the experiment.

Table 3: Vehicle operating characteristics with respect to the five strategies.

Indicator	Strategy 1	Strategy 2	Strategy 3	Strategy 4	Strategy 5
Mean of lane change location	102	250	305	298	358
SD of lane change location	8.48	7.95	6.52	9.15	7.49
Mean of speed (km/h)	77.175	82.356	75.054	76.012	80.125
SD of speed	0.981	0.802	0.072	1.575	1.055
Mean of acceleration (m/s^2)	-0.031	-0.021	-0.017	-0.064	-0.035
SD of acceleration	0.062	0.064	0.031	0.077	0.035
Mean of lateral placement (m)	0.016	0.051	0.035	0.054	0.010
SD of lateral placement	0.139	0.121	0.145	0.101	0.049

(2) Driving in the 5 Designed Scenarios. Each participant was assigned to drive in one of the five scenarios (corresponding to the five strategies). The scenario was randomly selected for each participant to increase the degree of randomness. The participants initially drove in the right lane, which was closed in the work zone. Each participant was given a 7-minute break between two consecutive simulations to maintain certain psychophysical conditions and minimize the effects of fatigue. Moreover, a mental status questionnaire (MSQ) (Kellogg et al., 1965) and social support questionnaire (SSQ) [31] were completed each time a participant completed a scenario. At the end, the participants were debriefed and paid. The time commitment for each participant was one hour.

3.5. Measures. Four dependent variables were considered as measures of the drivers' behaviors in the work zone: the lane change location, speed, acceleration, and lateral placement (distance between the center of the car and the right edge of the travel lane). Repeated-measures analysis of variance (ANOVA) was conducted to determine the effects of the within-subject factors of the speed, acceleration, and lateral placement. A Fourier transform was then used to evaluate the frequency change in the data. Finally, we used the analytic hierarchy process (AHP) to analyze the applications of the strategies based on the decision and behavior data, and suitable control strategies for different traffic situations were recommended.

4. Analysis and Results

The effects of the control strategies are represented by changes in the drivers' decisions and behaviors. In this paper, a driver's decision is described with regard to the location of the lane change, and a driver's behavior is described with regard to their speed, acceleration and lateral placement. The data about speeds, acceleration, and lateral placements were collected by driver simulator, then we use the MATLAB to calculate the mean of each participants' speeds, acceleration, and lateral placements in the control area per 5 m. Then the mean of speeds, acceleration, and lateral placements were calculated based on these original data. The courses were calculated from the start of the warning area to the start of the work zone. Because operating a car constitutes a continuous adjustment process, the drivers' mean and SD of each of the abovementioned driving behavior indicators are used to measure the operating performance in this research. Table 3 summarizes the vehicle operating characteristics with respect to the five strategies.

Table 3 shows several differences among the five strategies. For instance, the mean of lane change location was different in each strategy, which indicator the strategies have effective in drivers' decision. The mean of the speed in strategy 3 was the lowest among all five strategies, and the SDs of the lane change location, speed and acceleration in strategy 3 were the lowest among all five strategies. These results demonstrate that strategy 3 was more effective at improving both the driving stability (e.g., a low SD of the speed and a low SD of the acceleration) and the safety awareness (e.g., a low speed).

4.1. Effects of the Control Strategies on the Drivers' Decisions. The drivers' lane change locations are shown in Figure 4, in which the lane number denotes the lane of a vehicle in the simulator, and the values increase toward the right side of the road. Each scenario is represented by a different lane number; thus, lane numbers 1 through 9 indicate the vehicle positions in the different simulator scenarios. The mean of all drivers' lane changing locations was collected in this paper to analyze the influences of the five strategies on the drivers' obedience. However, the stability of the lane change was expressed by the lateral placement. Therefore, the SD of the drivers' lane changing location was not analyzed in this paper. The lane change location in each strategy is the mean of 32 drivers' lane change distances from the start of the control area. In strategy 1, drivers change lanes in the stretch beginning 100 m from the start of the control area, and the location moves with changes in the DMS arrangement and content. However, participants change lanes in the stretch beginning 300 m from the start of the control area in strategy 3, and this location is close to that in strategy 4, which means that prompts for drivers to change lanes beginning at 300 m and 400 m from the start of the control area have similar efficiencies. The location of the lane change was influenced by the location of the "change lane" sign, that is, drivers preferred to change lanes after seeing a "change lane" DMS. In addition, control strategies 3 and 4 had the same effect insomuch that the first locations of the "change lane" sign in the third and fourth DMSs had similar effects on the drivers' behaviors.

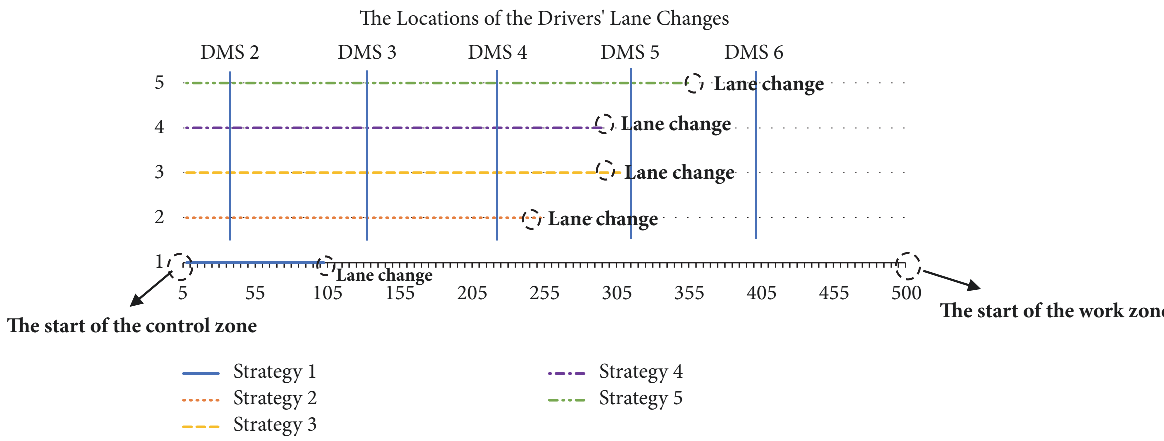


Figure 4: Locations of drivers' lane changes.

4.2. Effects of the Control Strategies on the Drivers' Behaviors. Next, to analyze the effects of the control strategies on the driving behavior, the descriptive statistics related to the speed, acceleration, and lateral placement in the five control strategies were analyzed. The speed is regarded as driving safety data, the acceleration is regarded as longitudinal stability data, and the lateral placement is regarded as lateral stability data. First, the individual differences (gender and age) were all tested to determine whether they covaried with the control strategies with an analysis of covariance (ACNOVA). In this and all subsequent analyses, the covariates were simultaneously entered into the model to assess the unique covariance of one covariate while accounting for any covariance in another covariate. Three age groups were identified: young (18-24), middle-aged (25-59), and old (> 60). This classification has been widely used in previous studies [32]. A regression analysis suggested the lack of a correlation between the age and gender distributions of the participants ($p > 0.05$), and an F-test statistical test ($F = 0.665$, $d.f. = 7$, $p = 1.701$) suggested the lack of a significant difference between the age and gender distributions of the participants. Then, the mean values of these variables were utilized to analyze the power spectral densities. The course of each indicator was described, and the frequency spectrum of each indicator was analyzed by a Fourier transform [33]. A low frequency concentration suggests that the indicator changes smoothly in the control area, and vice versa. The results of the analysis are presented below.

Effect of the Control Strategy on the Speed. The driver's control area speeds were tested by repeated-measures ANOVA, and the main effects of the control strategies reached significance ($F = 74$, $p = 0.001$). The courses of the driver's speeds are shown in Figure 5.

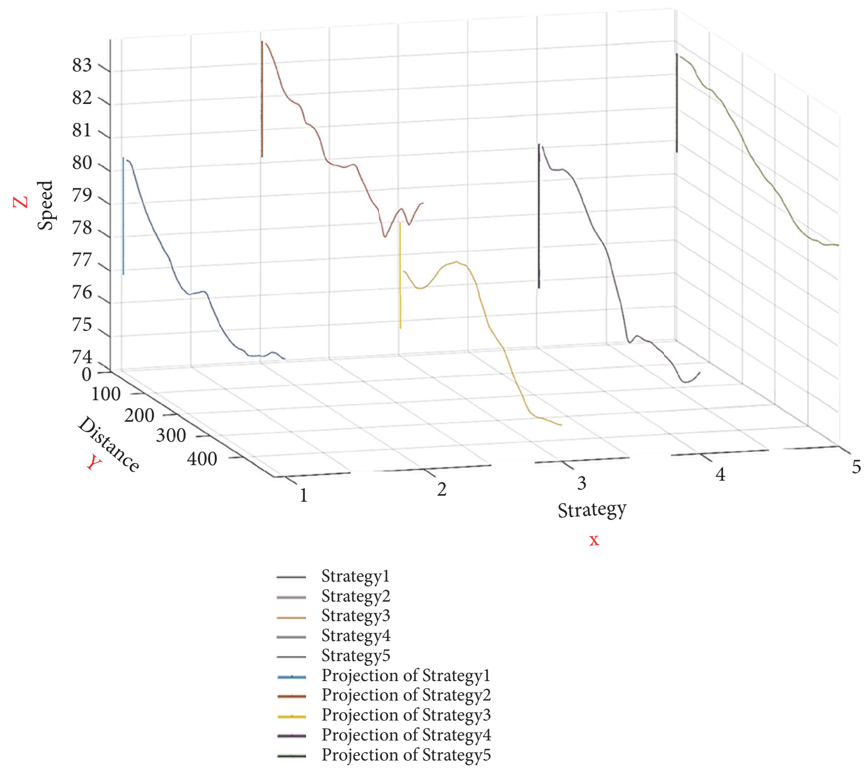
Previous studies have shown that DMSs have a significant effect on the vehicle speed. The same result was obtained in this study, as shown in Figure 5(a). The speed exhibits a downward course from the start of the control area. As shown by the projection of the speed curve in the Y-Z plane, the change in the speed was the lowest for strategy 3 and the largest for strategy 4. As shown in Figure 5(b), the drivers decreased their speed from DMS 2 to DMS 6 except in strategy 3, in which the drivers increased speed from DMS 2 to DMS 4. The speed may have been influenced by the speed limit signs (limit speed = 80 km/h) that were set at the start of the control area, and drivers likely increased their speed when they noticed that their speed was lower than the posted speed limit. Notably, the speed of the vehicle approaching the start of a work zone impacts the safety immediately; consequently, several studies have investigated the work zone safety based on the approaching speed [9]. Strategy 2 had the maximum approaching speed (82 km/h > 80 km/h), and strategy 3 had the lowest (75 km/h). Therefore, strategy 2 was excluded from the control strategies because the approaching speed exceeded the speed limit.

To investigate the frequency of the speed change, the speed curve was changed to the frequency spectrum using a Fourier transform [33]. The corresponding frequency spectra are shown in Figure 6. Strategy 3 and 5 exhibited a better smoothness performance in the speed change, and the strategy 5 has better performance than strategy 3. The frequencies were concentrated at lower frequencies, thereby indicating smooth speed changes in the control area, so the strategy 5 has the best speed control effective.

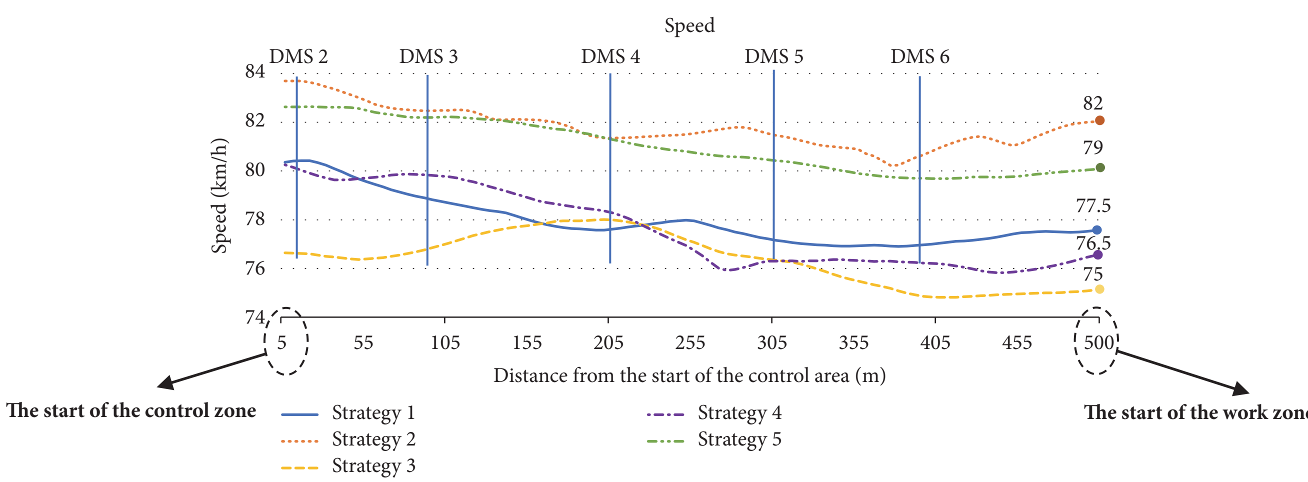
Effect of the Control Strategy on the Acceleration. The driver's acceleration in the different control strategies was tested by repeated-measures ANOVA, and the main effects of the control strategies reached significance ($F = 18.6$, $p = 0.001$). The acceleration courses are shown in Figure 7.

The acceleration courses differed among the five control strategies, as shown in the acceleration projection curves in the Y-Z plane. The acceleration exhibited the largest change for strategy 4 and the smallest change for strategy 5. As shown in Figure 7(b), the acceleration changed frequently, and the participants reduced their speed from DMS 2 to DMS 6.

To investigate the frequency of acceleration changes, the acceleration curve was changed to the frequency spectrum using a Fourier transform. The corresponding frequency spectra are shown in Figure 8. Strategies 1, 3, and 5 had high densities at lower frequencies, and the strategy 5 has better performance than strategies 3 and 1. The frequencies were



(a) Courses of the driver's speeds in the five control strategies (3D)



(b) Courses of the driver's speeds in the five control strategies (2D)

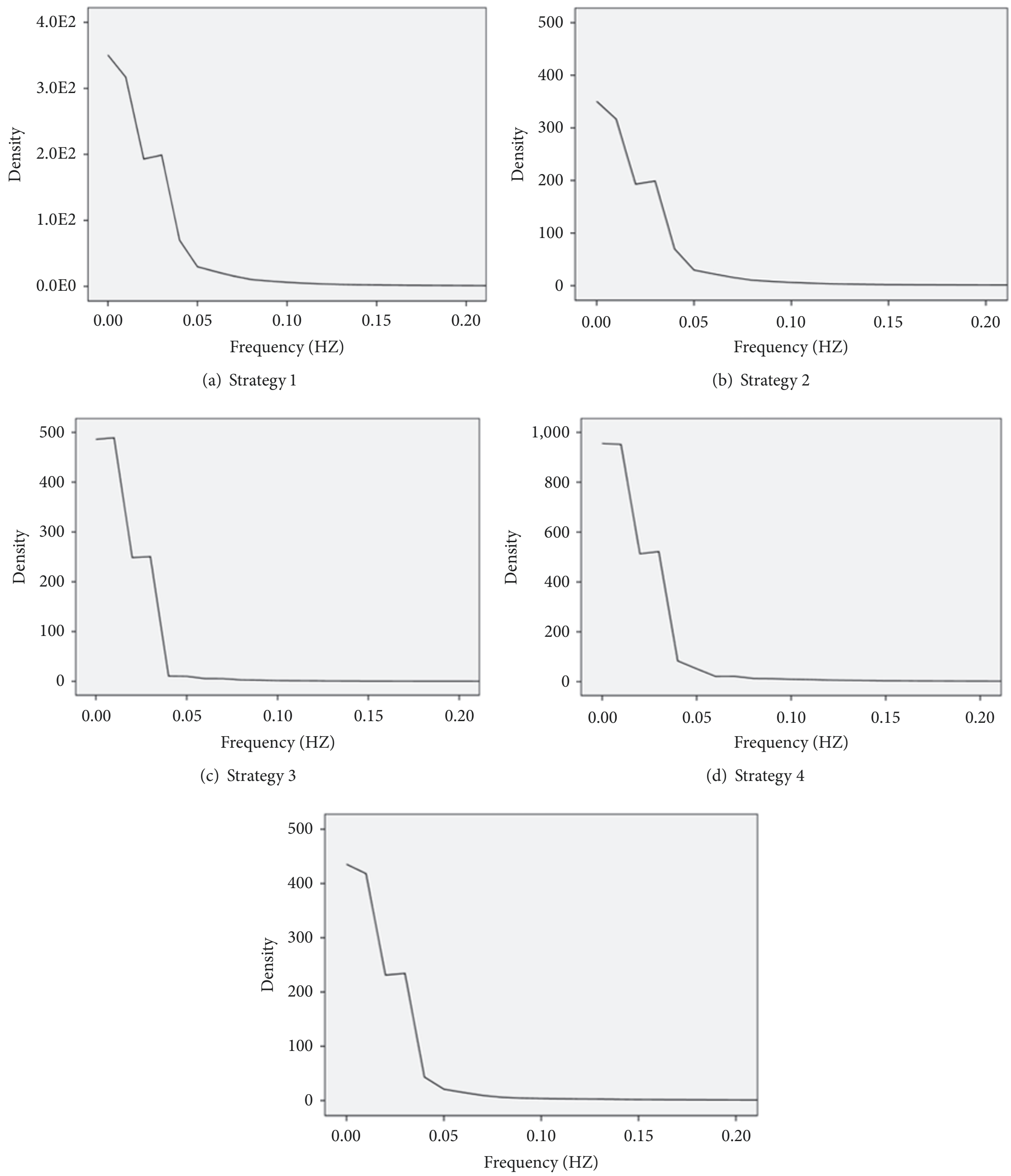
Figure 5: Courses of the driver's speeds in the five control strategies.

concentrated at lower frequencies, thereby indicating smooth acceleration changes in the control area, so the strategy 5 has the best acceleration control effective.

Effect of the Control Strategy on the Lateral Placement. The driver's lateral placements in the control area were tested by repeated-measures ANOVA, and the main effects of the control strategies reached significance ($F = 12.3$, $p = 0.001$). The lateral placement courses are shown in Figure 9.

As shown in Figure 9(a), the lateral placements exhibit the same courses among the different control strategies. As shown in projection of the lateral placement curves in the Y-Z plane, the lateral placement change was the smallest for strategy 3 and the largest for strategy 1. As shown in Figure 9(b), the drivers turned to the left from DMS 2 to DMS 4 and to the right after DMS 4, indicating that the drivers were conscientious about leaving a dangerous area (the work zone in the right lane).

To investigate the frequency of lateral placement changes, the lateral placement curve was changed to the frequency spectrum using a Fourier transform. The corresponding frequency spectra are shown in Figure 10. Strategies 1 and 5

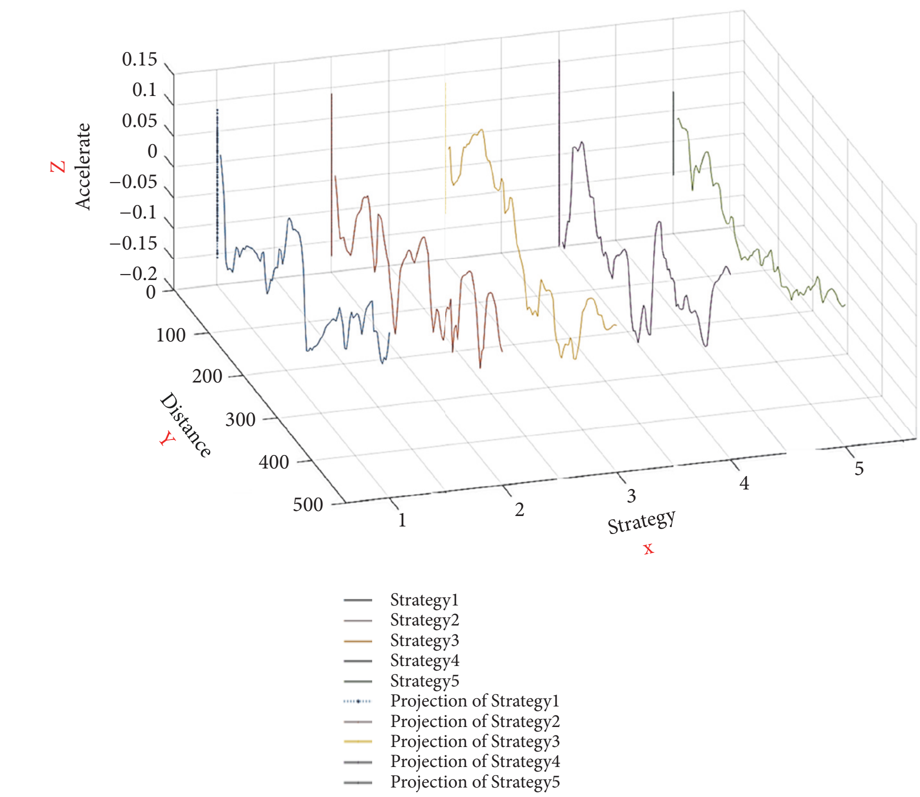


(e) Strategy 5

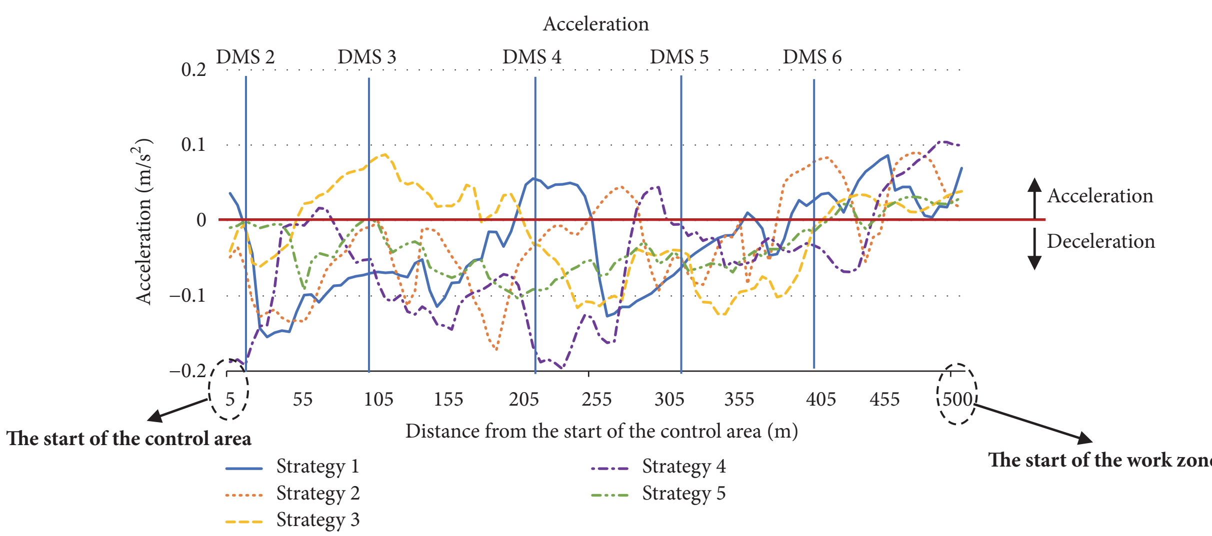
Figure 6: Frequency spectra of the driver's speeds.

showed high densities at lower frequencies, and the strategy 5 has better performance than strategy 3. The frequencies were concentrated at lower frequencies, thereby indicating smooth lateral placement changes in the control area, so the strategy 5 has the best lateral placement control effective.

4.3. Building an Evaluation Model of the Control Strategies Based on the AHP. As noted above, the five control strategies have different effects on the driving behaviors and driving decisions. The environment in a work zone is changeable. Workers should therefore choose appropriate strategies according to the traffic conditions. Speed is an



(a) Acceleration courses in the five control strategies (3D)

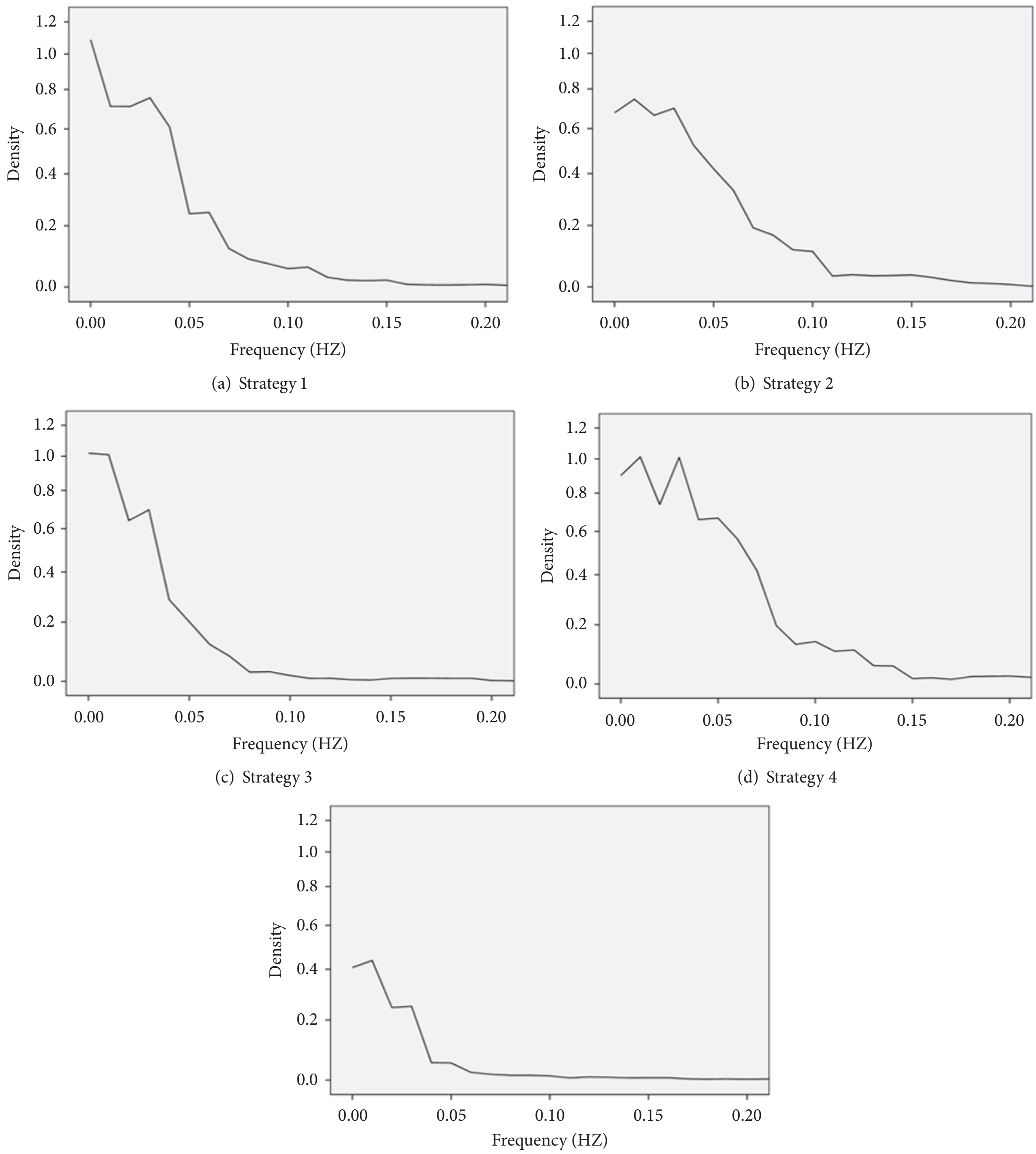


(b) Acceleration courses in the five control strategies (2D)

FIGURE 7: Acceleration courses in the five control strategies.

important indicator representing the work zone safety, and the traffic flow density is a typical indicator representing the speed conditions. Thus, we chose a traffic jam and free-flow traffic as different traffic conditions. The AHP was used to build the model for evaluating the control strategies based on the decision and behavior data. The four indicators selected above can be used as impact factors, where the total score of the strategy compliance is the evaluation result. The AHP model is shown in Figure 11. Among the control strategies, strategy 2 was excluded because the approaching speed exceeded the speed limit.

The next step in the AHP method is to obtain judgment matrix A. In this section, we used the Delphi method to evaluate the applicability of the different strategies under different traffic conditions. We obtained judgment matrices A1 and A2 for free-flow traffic and a traffic jam, respectively.



(a) Strategy 1

(b) Strategy 2

(c) Strategy 3

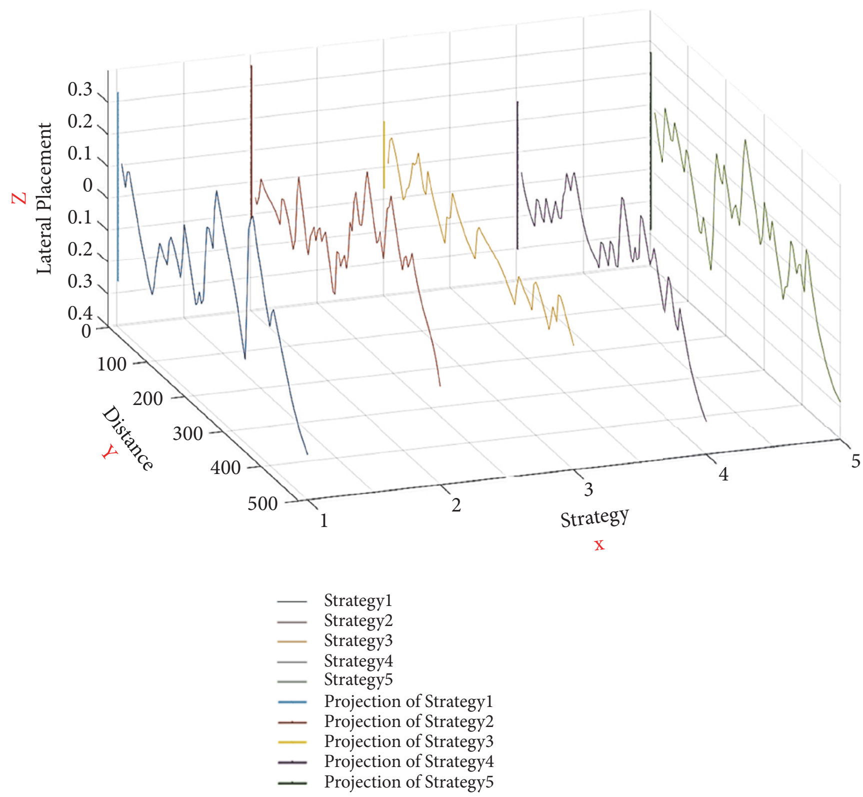
(d) Strategy 4

(e) Strategy 5

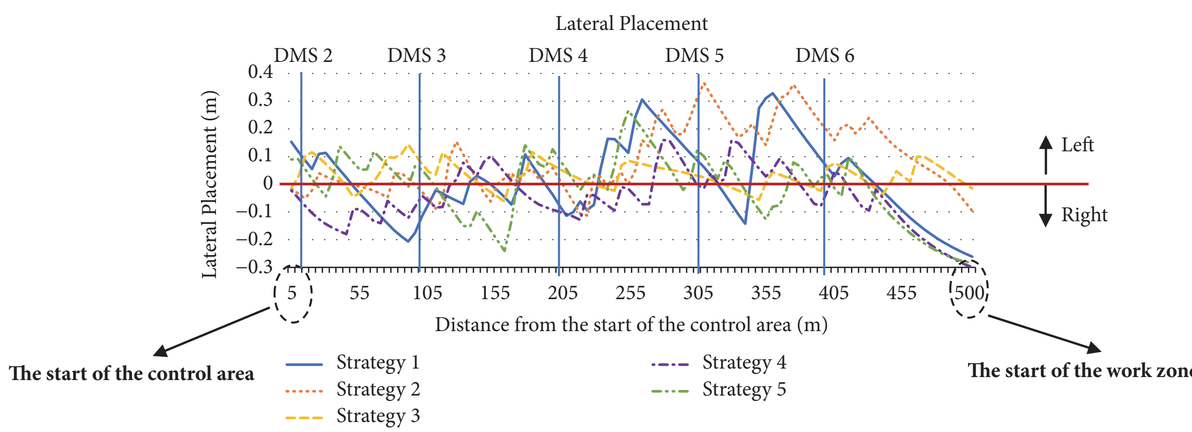
Figure 8: Frequency spectra of the driver's acceleration.

Then, we formed a questionnaire including 12 questions, as shown in Table 4.

Next, we asked 10 traffic engineering teachers to complete the questionnaire. We collected the results of every questionnaire and sent them to each teacher. After becoming aware of the complete results, they responded to the questionnaire again. This step was repeated 3 times. In other words, the teachers responded to the questionnaire 3 times. Upon completing the questionnaire for the first time, they responded to the questionnaire according to their own opinion; upon completing the questionnaire for the second and third times, they considered the other teachers' scores before responding. Finally, we retained the results of the third questionnaire, calculated the average values provided by the 10 teachers, and



(a) Lateral placement courses in the five control strategies (3D)



(b) Lateral placement courses in the five control strategies (2D)

Figure 9: Lateral placement courses in the five control strategies.

then rounded the results. In this manner, judgment matrices A1 and A2 were obtained, as shown in Table 5.

Referring to the method introduced by Chen in his dissertation [34], we calculate the maximum eigenvalues $\lambda_{\max(A1)} = 4.04$ and $\lambda_{\max(A2)} = 4.04$ in addition to the coincidence indicator $CI_{A1/A2} = (\lambda_{\max} - n)/n - 1 = 0.013$. Normally, we obtain RI = 0.89 when n = 4 [34]; thus, CR = CI/RI = 0.015 < 0.1. Therefore, the consistency between the judgment matrices A1 and A2 is considered good. Then, we perform normalization on the matrix A columns according to $aij = aij/\sum_{i=1}^{n} aij$ to obtain A1' and A2' as follows:

$$
\begin{gathered}
A1' = \begin{bmatrix} 0.21 & 0.19 & 0.3 & 0.3 \\ 0.64 & 0.58 & 0.5 & 0.5 \\ 0.07 & 0.12 & 0.1 & 0.1 \\ 0.07 & 0.12 & 0.1 & 0.1 \end{bmatrix}; \\
A2' = \begin{bmatrix} 0.57 & 0.64 & 0.5 & 0.5 \\ 0.19 & 0.21 & 0.3 & 0.3 \\ 0.12 & 0.07 & 0.1 & 0.1 \\ 0.12 & 0.07 & 0.1 & 0.1 \end{bmatrix}.
\end{gathered}
\tag{2}
$$

Table 4: Index pairwise comparison questionnaire for the AHP method in the strategy compliance evaluation.

NOTE: please fill in this questionnaire according to following judgment criterion table.	
Score	Meaning
1	The two indices are equally important
3	The first one is slightly more important than the second one
5	The first one is obviously more important than the second one
7	The first one is strongly more important than the second one
9	The first one is extremely more important than the second one
2, 4, 6, 8	The mid-value between the above judgments
Compare the indices i and j to obtain judgment bij; compare the indices j and i to reciprocal Obtain judgment $bji = 1/bij$	
(1) When there is free traffic flow in work zones: (1) The location of lane change is compared to the entering speed ( ) (2) The location of lane change is compared to the mean of accelerator ( ) (3) The location of lane change is compared to the mean of lateral placement ( ) (4) The entering speed is compared to the mean of accelerator ( ) (5) The entering speed is compared to the mean of lateral placement ( ) (6) The mean of accelerator is compared to the mean of lateral placement ( )	
(2) When there is traffic jam in work zones: (1) The location of lane change is compared to the entering speed ( ) (2) The location of lane change is compared to the mean of accelerator ( ) (3) The location of lane change is compared to the mean of lateral placement ( ) (4) The entering speed is compared to the mean of accelerator ( ) (5) The entering speed is compared to the mean of lateral placement ( ) (6) The mean of accelerator is compared to the mean of lateral placement ( )	

Next, we add the entire set of values in a row $a_i = \sum_{j=1}^{n} aij$ to obtain W1' = [1, 2.2, 0.4, 0.4] and W2' = [2.2, 1, 0.4, 0.4]. Then, we obtain the weight vector $W = Wij/\sum_{i=1}^{n} Wij$.

Thus, W1 = [0.25, 0.55, 0.1, 0.1], and W2 = [0.55, 0.25, 0.1, 0.1]. Moreover, we reference the location of the lane change, the approaching speed, the mean acceleration, and the mean lateral placement as a hierarchy analysis matrix. The data for the different strategies are shown in Table 5.

According to Table 6, we obtain judgment matrices B1-B4 for the different strategy indicators as follows:

$$B1 = \begin{bmatrix} 1 & \frac{1}{3} & \frac{1}{3} & \frac{1}{5} \\ 3 & 1 & 1 & \frac{1}{3} \\ 3 & 1 & 1 & \frac{1}{3} \\ 5 & 3 & 3 & 1 \end{bmatrix};$$

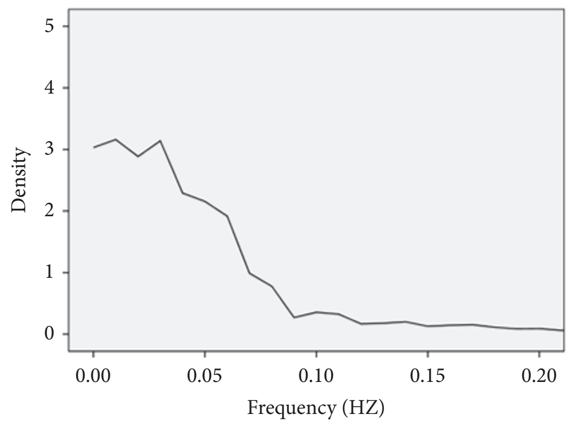
$$B2 = \begin{bmatrix} 1 & 1 & 1 & 3 \\ 1 & 1 & 1 & 3 \\ 1 & 1 & 1 & 3 \\ \frac{1}{3} & \frac{1}{3} & \frac{1}{3} & 1 \end{bmatrix};$$

$$B3 = \begin{bmatrix} 1 & 3 & \frac{1}{3} & 1 \\ \frac{1}{3} & 1 & \frac{1}{5} & \frac{1}{3} \\ 3 & 5 & 1 & 3 \\ 1 & 3 & \frac{1}{3} & 1 \end{bmatrix};$$

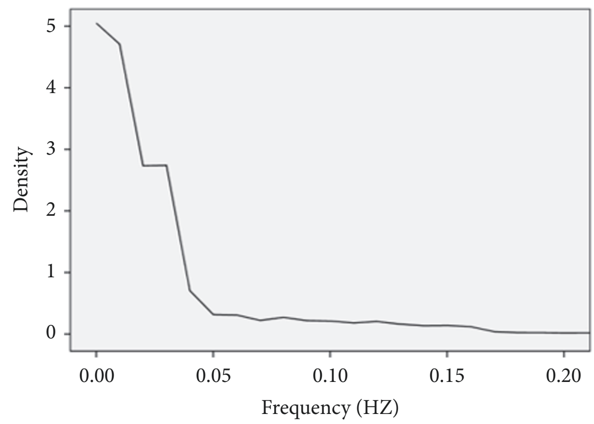
$$B4 = \begin{bmatrix} 1 & 3 & 5 & 1 \\ \frac{1}{3} & 1 & 3 & \frac{1}{3} \\ \frac{1}{5} & \frac{1}{3} & 1 & \frac{1}{5} \\ 1 & 3 & 5 & 1 \end{bmatrix}. \tag{3}$$

Using the same method, we obtain the vectors Υ'_B shown in Table 7.

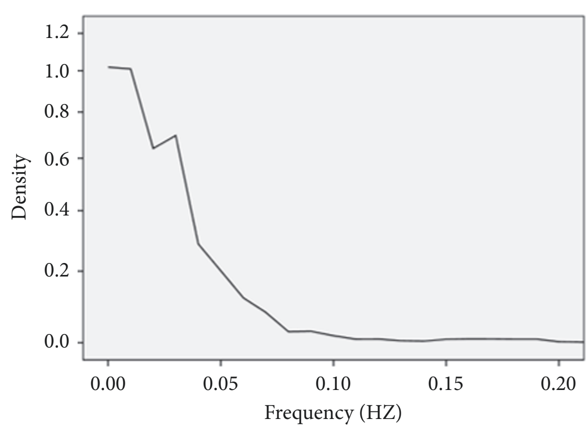
Subsequently, we obtain the final weighting vector Υ with $W * \Upsilon'$. Each strategy is weighted as follows: for free-flow traffic and a traffic jam: $\Upsilon_{\text{free-flow traffic}} = [0.25, 0.28, 0.17, 0.23]$ and $\Upsilon_{\text{traffic jam}} = [0.17, 0.28, 0.2, 0.3]$, respectively. Notably, under traffic jam conditions, it is very difficult to perform a lane change; accordingly, the driver behavior will be very different from that under free-flow conditions. Therefore, the reliability of the total score under traffic jam conditions is puzzling, as it is simply an exploration of this



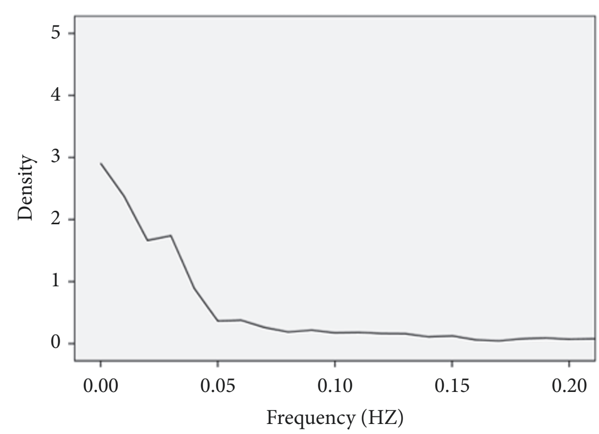
(a) Strategy 1



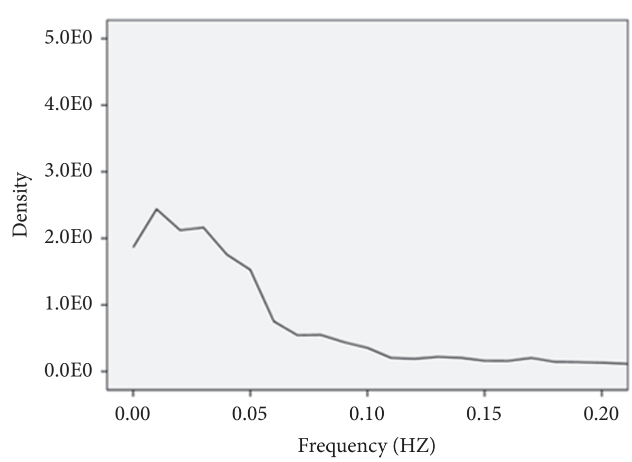
(b) Strategy 2



(c) Strategy 3



(d) Strategy 4



(e) Strategy 5

FIGURE 10: Frequency spectra of the driver's lateral placement changes.

phenomenon under traffic jam conditions. Consequently, the reliability of the total score under traffic jam conditions will be analyzed in a future study. Instead, the total score under free-flow conditions is primarily investigated herein. Furthermore, the method used in this paper can also be used for analyzing the total score under traffic jam conditions.

5. Discussion

The objective of this paper was to verify the more reasonable installation positions and control strategies of DMSs. The overall speed-limited compliance for strategies 1, 2, 3, 4, and 5 was calculated to be 65%, 40%, 83%, 77%, and 60%, respectively. Some of these compliance rates are higher than

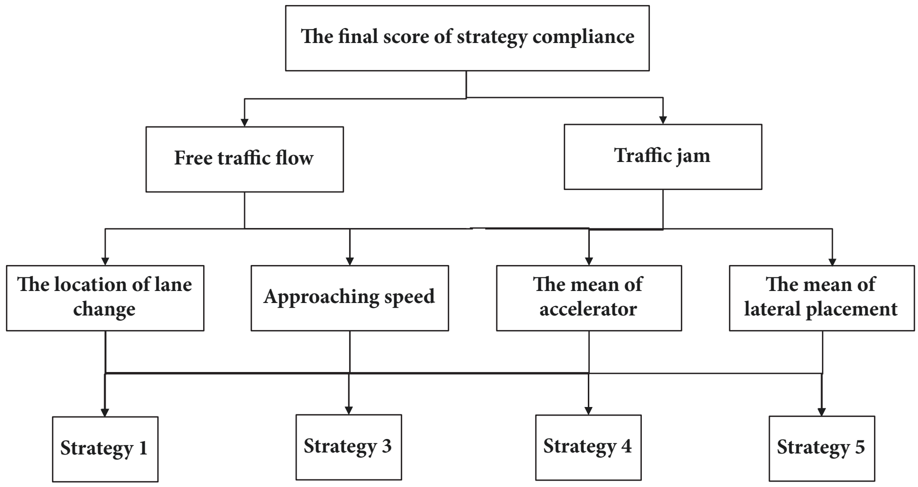


FIGURE 11: Hierarchical structure in the AHP for strategy compliance.

TABLE 5: Judgment matrices A1 and A2.

A1 (Free-flow traffic)		Location of the lane change B1	Approaching speed B2	Mean acceleration B3	Mean lateral placement B4
Location of the lane change	B1	1	1/3	3	3
Approaching speed	B2	3	1	5	5
Mean acceleration	B3	1/3	1/5	1	1
Mean lateral placement	B4	1/3	1/5	1	1
A2 (Traffic jam)		B1	B2	B3	B4
Location of the lane change	B1	1	3	5	5
Approaching speed	B2	1/3	1	3	3
Mean acceleration	B3	1/5	1/3	1	1
Mean lateral placement	B4	1/5	1/3	1	1

TABLE 6: Data for the different strategies.

Indicator	Strategy 1	Strategy 2	Strategy 3	Strategy 4
B1: Location of the lane change	100	298	300	370
B2: Approaching speed (km/h)	77	75	76	80
B3: Mean of acceleration (m/s^2)	-0.031	-0.017	-0.06	-0.035
B4: Mean lateral placement (m)	0.01	0.03	0.05	0.01

TABLE 7: Vectors Υ'_B.

B	Strategy 1 C1	Strategy 2 C2	Strategy 3 C3	Strategy 4 C4
B1	0.08	0.2	0.2	0.52
B2	0.3	0.3	0.3	0.1
B3	0.2	0.08	0.52	0.2
B4	0.39	0.15	0.07	0.39

those reported in previous studies (e.g., 40-70%; [35]). High compliance rates mean that the drivers were cautious and tended to comply with the control strategies. In addition, the high compliance rates obtained in this paper support the notion that people behave better when they know that they are being observed in a driving simulator.

First, the results provided evidence of the effects of different control strategies on lane change decisions before entering work zones. The location of the lane change was influenced by the location of the "change lane" sign, and drivers preferred to change lanes after seeing a DMS showing "change lane" content. In addition, control strategies 3 and 4 had the same effect insomuch that the first locations showing "change lane" content in the second and third DMSs had similar effects.

Second, the results demonstrated that the control strategy also affects the driving behavior, including the speed, acceleration, and lateral placement. Specifically, the speed decreased from the start of the control area. As shown by the projection of the speed curves in the Y-Z plane, the speed was the slowest for strategy 3 and the highest for strategy 4. The work zone approaching speed was the most important factor for the driving safety. Thus, strategy 2 was excluded from among the control strategies. Notably, the acceleration and lateral placement were used to test the driving stability in this study. The results showed that the control strategy influenced the acceleration; moreover, the acceleration change was the largest for strategy 4 and the smallest for strategy 5. Strategy 4 showed a higher density at higher frequencies than the other strategies, which means that the drivers maintained smooth acceleration in strategies 1, 3, and 5. The results for the lateral placement were different. The change in the lateral placement was the smallest for strategy 3, and the largest change occurred for strategy 1. In the frequency spectrum, strategies 1 and 5 showed a higher density at higher frequencies than the other strategies, which means that the drivers maintained smooth lateral placement in strategies 3 and 4. The results were different for the acceleration and lateral placement changes; one possible reason for this could be that drivers can focus on only one operation during driving (i.e., horizontal or longitudinal operations).

Work zone workers should choose the most suitable strategy from those mentioned above based on the conditions. Thus, we used the AHP to analyze the applications of the control strategies based on the decision and behavior data. Using the decision and driving behavior as the evaluation objects, the four indicators selected above can be used as impact factors, where the total score of the strategy compliance is the evaluation result. The weight vectors are $\Upsilon_{\text{free-flow traffic}} = [0.25, 0.28, 0.17, 0.23]$ and $\Upsilon_{\text{traffic jam}} = [0.17, 0.28, 0.2, 0.3]$; these results show that strategy 4 is not suitable for free-flow traffic in work zones, while strategies 5 and 3 are suitable for traffic jams in work zones. Strategy 3 is suitable for both free-flow traffic and traffic jams. The occurrence of the first sign that contains lane change content is key to the driver's decision. The lane change position should be moved gradually closer to work zones with increasing traffic flow. Based on the results, workers can reliably choose the most suitable strategy depending on the traffic conditions to maintain safety and stability in work zones.

A driving simulator experiment was conducted in this study; accordingly, as with any driving simulator study, there are certain limitations inherent to this approach. The driving behavior may not match the normal driving behavior because the participants know that they are being observed. The data validity has consistently been found to impact the experiment [36]. Therefore, to decrease the gap between the reality and the simulation, scenarios were designed to represent real segments of highway whenever possible to improve the validities of the scenarios. Moreover, to address the problem in which the participant exhibits a lack of risk while driving in the simulator, the experimenters were encouraged to drive realistically by allowing them to become familiarized with the drive, increasing the lengths of the scenarios, and providing verbal instructions. Through these practices, the validity of the simulation approach used in this paper has been proven in many previous studies (e.g., [37]). To date, more than 300 drivers in driving experiments have been utilized to evaluate the validity of this driving simulator through questionnaires. The evaluation items included characteristics such as the realistic feel of the accelerator and brakes and their speed perception. The results of the questionnaire ratings revealed that the majority of drivers agreed with the validity of this driving simulator. Moreover, the driving effects found in simulators tend to be larger than those found in natural experimental settings [38] However, those effects do follow the same trends in both types of experiments (i.e., simulated and natural), thereby providing a good relative validity. Hence, given the ability of the current study to control the scenario design, the majority of the limitations on our method were minimized. Additionally, considering the need to collect performance measures of drivers' responses under potentially hazardous situations without putting participants at risk, the existing limitations are acceptable.

6. Conclusions

Several factors contribute to the number of work zone fatalities, but one critical method that can reduce the number of such fatalities is to increase the driver's awareness to make correct driving decisions by implementing control strategies. Accidents and injuries in work zones could be greatly reduced by identifying and eventually implementing effective strategies with DMSs to improve the driving behavior and enhance safety in work zones.

Based on a driving simulator study, this study mainly considered various DMS control strategies. This study investigated the effects of different control strategies on driving decisions and behaviors, and the results showed that control strategies with DMSs influence reductions in the driving speed and improvements in the driving stability. These control strategies are useful for reducing the driving speed and improving the driving stability by changing the content ("change lane" versus "go straight") and locations of DMSs. Moreover, strategy 4 is not suitable for free-flow traffic in work zones, while strategies 5 and 3 are suitable for traffic jams in work zones.

The results also showed that the different control strategies have different effects on the speed, acceleration, and lateral placement. Workers can choose the most suitable strategy for different work zone traffic situations. The occurrence of the first sign that contains lane change content is key to the driver's decision. The approaching speed is an important indicator representing the safety within the work zone, and the traffic flow density is a typical indicator representing the speed conditions. In past studies, researchers have always chosen the traffic flow density as the traffic environment indicator (Li, et al., 2018). Thus, we choose a traffic jam and free-flow traffic as the traffic conditions. Consequently, workers can choose the most suitable strategy to effectively maintain the work zone safety and stability based on the present traffic conditions. In this study, strategy 3 is suitable for both traffic jam and free-flow traffic conditions, where the first occurrence of "change lane" content is on the second DMS. This result can be considered for the design of DMSs in work zones to further enhance safety.

An effective control strategy is required to connect vehicles in work zones to smart devices in the pilot stage. In this study, the control strategies were designed based on DMSs that can be used in work zones to enhance the driving safety and stability. Future studies should also investigate new interventions in combination with DMSs and their effectiveness at increasing driver compliance; one such invention could be the presence of law enforcement personnel or vehicles in or ahead of road construction zones. Then, field studies should investigate the usefulness of those strategies in real work zones and test how those strategies affect driving decisions and behaviors in work zones.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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