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Research Article

Exploring the Effects of Signs' Design and In-Vehicle Audio Warning on Driver Behavior at Flashing-Light-Controlled Grade Crossings: A Driving Simulator-Based Study

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The complex environment at grade crossings and the severe collision consequences give rise to the concern of safety condition at crossings among traffic control authorities. Optimizing conventional devices and applying emerging technologies are worthwhile measures to improve the safety conditions at grade crossings. In this study, a flashing-light running (FLR) warning system was proposed to reduce crossing violation and improve performances of drivers at flashing-light-controlled grade crossings (FLCGCs). Forty-four fully licensed drivers aged between 30 and 48 years participated in a driving simulator study to investigate the efficacy of two countermeasures of the system: proposed design of signs and pavement markings (PSM) for grade crossing, and two-stage in-vehicle audio warning (IVAW) technology. A range of flashing light trigger timing and two foggy conditions were designed in this experiment to test the system applicability. Drivers' gender and vocation were considered as well to examine drivers' adaptation to the new proposed system. Five variables were collected and analyzed in this study to investigate the effectiveness of the system, i.e., drivers' compliance, approaching mean speed, brake reaction time, deceleration, and red-to-crossing time. Results showed that drivers' driving performances were improved in both PSM only condition and PSM + W condition. The FLR warning system could eliminate the negative effects of foggy weather and reduce gender differences in driver behaviors to some extent. These findings suggested that the FLR warning system has a potential to reduce the probability of grade crossing collisions.

1. Introduction

Grade crossings where the roadway and railroad tracks intersect have created serious conflicts between trains and vehicles. In 2004, 729 accidents involving grade crossings occurred in China, with a total of 513 casualties and 2292 hours of interruption on the main line operation, resulting in direct economic losses of up to ¥12 million (around 1.68 million USD) [1]. Similar figures have been observed in other countries as well. In Europe, grade crossing crashes led to 604 fatalities and casualties in 2011, which accounted for more than one quarter of all railway crashes [2]. In the US, collisions at grade crossings are frequent, with 267 fatalities and 826 injuries related to grade crossings in 2018 [3]. Therefore, grade crossing safety has been one of the top worldwide issues that attracts the attention of relevant transport authorities and the public [4, 5]. Among all the causes of grade crossing collisions, driver behavior on approaching to grade crossings is one of the main contributors [6], indicating the need for countermeasures targeting at drivers to improve the safety condition at grade crossings.

In China, the grade crossings could be divided into guarded crossings and nonguarded crossings, and about 62% of them are nonguarded crossings [7], where more driver errors and violations could be observed. Regarding the nonguarded crossings, two kinds of crossings can be defined according to the warning devices provided, e.g., passive crossings and active crossings. Passive crossings provide static warning devices only, e.g., STOP signs, pavement markings, and advanced warning signs. Drivers are required to observe the crossing and check if there are trains approaching before they cross. Different from passive crossings, active crossings provide active warning devices that can be real-time adjusted, e.g., flashing light or a gate with flashing light. Drivers are not allowed to enter the crossing if the gate is dropped down and/or the red lights are flashing. Compared with passive control, lower crash rates and greater compliance at grade crossings with active control devices have been reported in both historical crash data analyses and driving simulator studies [5, 8, 9]. However, drivers may fail to comply with active grade crossing control for a variety of reasons. For flashing-light-controlled crossings, driver errors and violations have been frequently observed due to the absence of physical obstructions [10]. However, little attention has been paid to such kind of grade crossings. Ideally, grade separation is the most effective solution for avoiding grade crossing conflicts, but it cannot be widely applied due to the high cost involved [11]. Therefore, there is a large demand to develop lower-cost technologies or devices to improve drivers' compliance and behavior at flashing-light-controlled grade crossings (FLCGCs).

When developing effective FLCGCs, a thorough understanding of drivers' crossing behavior is of great importance. Due to the overestimated remaining time and misunderstanding of the warning information, at least 55% of drivers still chose to cross the tracks even when the red lights were flashing [10, 12]. Though without yellow signal, there is a region of roadway existing upstream of crossings at the onset of flashing light, which is similar to the "dilemma zone" of roadway intersections. When the driver encounters a signal change, he or she may neither stop nor cross successfully due to a high approaching speed, underestimating the required braking distance or exercising an aggressive behavior [13]. Drivers' incorrect decisions at the onset of flashing light may lead to flashing-light running (FLR) violations, and drivers' sudden stop action in front of the crossings may result in rear-end collisions with the vehicles behind them. Furthermore, instead of waiting for the end of the flashing lights, some drivers tended to cross the track once the train left the crossing while the red lights were still flashing. This kind of behavior may put the drivers in great risk if a second train was approaching [14].

Many safety approaches to decrease FLR violations at grade crossings have focused on countermeasures applied either on the intersecting road or the grade crossing itself (e.g. signs, pavement markings, and flashing lights' warning time). It can be inferred that drivers can perceive hazards associated with a grade crossing by signs and markings, and thus change their travel speeds to achieve a safe and smooth driving process [15–18]. However, static signs and markings provide limited help in assisting drivers to make stop/go decisions. Meanwhile, the role of signs and markings is degraded under adverse weather conditions, such as foggy weather. In-vehicle audio warning (IVAW) countermeasure based on intelligent vehicle infrastructure cooperative (IVIC) technology can make up for the defects of static signs and markings [19]. Many studies have confirmed that IVAW can improve driver behavior. However, the lack of the ability to inform drivers about failures of the IVAW could counterbalance the safety benefits. There is no doubt that the reliability of traditional signs and markings is irreplaceable in comparison to the IVAW. Nevertheless, few research studies to date have considered the mutual assistance of these two countermeasures to improve the safety condition of grade crossings.

2. Literature Review

This paper proposed two novel low-cost grade crossing treatments. Traffic signs and pavement markings are the basis of traditional traffic management. IVAW is an emerging and popular intelligent management technique. This paper aims to propose a more reasonable design and placement of signs and markings and, on this basis, propose a matched IVAW program. It is assumed that the mutual assistance of these two countermeasures can improve the reliability and effectiveness of the flashing-light running (FLR) warning system.

2.1. A Series of Signs and Pavement Marking Countermeasures. In China, there is a lack of grade crossings design standards to match the information requirement of drivers. The shortcomings of signs and markings practice have not been adequately addressed. The Manual on Uniform Traffic Control Devices (MUTCD, USA) [20] suggests that all grade crossings (unless a four-quadrant gate system) should install the dynamic envelope markings (DEMs) to indicate the clearance requirement of the train. The DEMs are used to depict dangerous areas where the vehicles and the train may collide. Moreover, if automatic gates are not presented and if there are two or more tracks at one grade crossing, a supplemental number of tracks plaque should be mounted below the crossbuck sign to indicate the possibility of multiple trains crossing. However, no similar requirements were applied in Chinese relevant standards.

In general, grade crossing warning sign is placed near the grade crossings to remind drivers of a potential stop. Drivers may understand that the sign is associated with a crossing, but they might not understand its behavioral implications [21]. The information required by the driver depends on the nature of the crossing. In the case of FLCGCs, drivers do not need to recognize the hazard, but they do need to prepare to slow down and pay attention to the change of flashing light. Therefore, it is necessary to provide drivers with the information about the type of crossing ahead. The 'Signal Ahead' sign and pavement marking (see Figures 1(a) and 1(b)) have been listed in the MUTCD to alert drivers of a

(a) (b) (c)

Figure 1: Signal ahead sign and marking at a signalized intersection, flashing-light ahead sign at a grade crossing. (a) Signal ahead sign (MUTCD); (b) signal ahead marking (MUTCD); and (c) flashing-light ahead sign (New Zealand, Australia).

signalized intersection in front. Previous studies have shown that these could help drivers make proper stop/go decision and reduce the dilemma zone effect [22]. Flashing-light ahead sign has been widely adopted in New Zealand and Australia (see Figure 1(c)). However, it is not yet very clear where the sign should be positioned at grade crossings and how the sign can impact drivers' crossing behavior.

The advance placement distance of grade crossing warning signs can be calculated based on the design speed. In China, signal ahead and grade crossing warning sign are typical signs that warn drivers of the potential stop situation. The advance placement distance is based on the 2011 AASHTO Policy with the stopping sight distance (as shown in the following equation (1)) subtracting the sign legibility distance of 55 m.

$$\mathrm{SSD} = 0.278Vt + 0.039\frac{V^2}{a}, \tag{1}$$

where SSD is the stopping sight distance (m); V is the design speed (km/h); t is the brake reaction time (2.5 s); and a is the deceleration rate (3.4 m/s^2).

Another typical condition in MUTCD is absent in the Chinese standard. The condition considers locations where the road user must spend some time to adjust speed and change lanes in heavy traffic because of a complex driving situation. The distances are determined by providing the driver with a premaneuver time of 14.0 to 14.5 seconds for vehicle maneuvers (2011 AASHTO Policy, decision sight distance as shown in equation (2)). Similarly, a sign legibility distance of 55 m is considered.

$$\mathrm{DSD} = 0.278Vt + 0.039\frac{V^2}{a}, \tag{2}$$

where DSD is the decision sight distance (m); V is the design speed (km/h); t is the premaneuver time (between 14.0 s and 14.5 s); and a is the deceleration rate (3.4 m/s^2).

It should be noted that MUTCD does not specify how to optimize the warning sign placement in terms of traffic safety and operation. This paper proposed the application of a series of signs and pavement markings for FLCGCs.

2.2. In-Vehicle Audio Warning Countermeasure. Considerable research and innovation has occurred on IVAW countermeasure for crossing safety. Larue et al. [23] found that IVAW resulted in higher compliance rates when a train was approaching the passive crossing. The IVAW also resulted in lower speeds closer to the crossing, faster brake response times, and larger safety margins at passive crossings [24, 25]. However, the IVAW had limited effect at active crossings, and an important reason is that the verbal warning was provided when the flashing lights were activated and it was hard for drivers to collect sufficient information and make a quick response [23]. Therefore, the delivery time of warning messages could seriously influence the effectiveness of the warning system [26, 27]. In fact, drivers could avoid most violations if the warning messages were delivered in advance of the flashing light activation, especially in the case of short time to stop line when the flashing light was activated. In terms of the warning systems proposed in prior studies, auditory warning messages are usually used to remind drivers of train approaching and require drivers to take appropriate actions immediately. The system that only provides an emergency warning message is called single-stage advance warning systems (SSAWS). The SSAWS only published the warning once, but it left drivers with little time to identify and respond to the possible hazardous situation. Nevertheless, the two-stage advance warning system can help drivers maintain safer driving conditions by providing a piece of forecast information that draws drivers' attention at the first stage [28, 29]. The considerable lower cost of IVAW application compared to conventional active devices provides extra motivation for their use [30, 31], and their effectiveness will be examined in this study.

2.3. Impacts of Foggy Conditions on Driver Behavior. The effects of different weather conditions on traffic crashes have been paid much attention in the field of transportation research [32, 33]. Among the adverse weather conditions, fog is the most hazardous one, which is more likely to result in high crash frequency (19.54%) and severe crash outcome [34, 35]. Driving in fog can be risky for drivers of all levels of abilities as the fog leads to a substantial reduction in visibility [36]. Among all the adaptions of driving behaviors in fog, changing speed is the most typical one. Drivers tended to approach a grade crossing at speeds that were too high for them to stop and, therefore, high speed has become a major contributing factor in many of the crashes that occurred in foggy conditions [37]. Although driving behaviors in fog weather have been investigated in many studies, few of them have addressed how drivers' behaviors at highway-rail grade crossings were affected by fog. Additionally, it is expected that the proposed countermeasures at grade crossings could offset the negative impacts of fog weather and provide more safety benefits for drivers. The common negative impact of various adverse weather conditions mainly comes from the impairment on drivers' visibility and the increased mental workload while driving. Therefore, the investigation of the effectiveness and reliability of the proposed countermeasures in fog could also indicate their applicability potential in other adverse weather conditions.

2.4. Impacts of Driver Characteristics on Driver Behavior. Driver characteristics have been found to be related to unintended human errors, intentional actions, and risk-seeking behaviors on road [38–40]. Among driver characteristics, gender [5, 41] and vocation [42, 43] were acknowledged to differentiate drivers' performances with a great variance. Several studies reported that female drivers committed fewer violations than male drivers [41, 44, 45]. The violation behaviors were strongly related to collision likelihood and consequently, male drivers were more likely to be involved in injuries and fatalities crashes compared to females [46, 47]. Besides, drivers' vocation was another factor related to traffic violations and road crashes [48]. Professional drivers (such as taxi, bus, or truck drivers) had a high probability of traffic crashes due to a high exposure on road and the high possibility of fatigue driving [49]. Moreover, professional drivers may perform differently from nonprofessional drivers because of different levels of driving skills. Generally, taxi drivers were more experienced, more sensitive to the impending changes in the road geometry, and behaved more skillfully in both longitudinal and lateral vehicle control than private car drivers [50]. Although many previous studies analyzed drivers' gender and vocation characteristics in traffic violations and crash-involvement risk, it is still not clear whether there are gender and vocation differences on driving behaviors in the process of approaching a grade crossing.

2.5. Objectives of This Study. In summary, the current traffic signs and pavement markings for FLCGCs of China provide insufficient information to drivers, and the design of the United States and Australia is worth learning. For IVAW, the existing literature rarely referred to two-stage IVAW, especially when it is used with traffic signs. Additionally, drivers' characteristics and foggy conditions contribute to different driving behavior patterns. However, their effects on driver behavior in the process of approaching a grade crossing remain unclear. Toward this end, this paper presents a driving simulator experiment study that aims at investigating the effectiveness of the lower-cost FLR warning system at the flashing-lights-controlled grade crossings. The research framework of the study is presented in Figure 2. Compared with previous studies, this paper improves current knowledge in four aspects: (1) this paper proposes a flashing-light running (FLR) warning system that includes improved signs and markings (PSM) design and a two-stage IVAW; (2) instead of designing some flashing light trigger timing (FLTT), this study focuses on drivers' stop/go decisions under a set of continuously scattering points within the predefined range of FLTT; (3) a range of FLTT is designed in combination with a binary choice of heavy fog conditions to test the applicability of FLR warning system in adverse visibility condition; and (4) driver characteristics, e.g., gender and vocation, are considered in this study to examine different drivers' adaptation to the new proposed PSM and IVAW.

3. Method

3.1. Participants. Forty-seven full-licensed participants were recruited to participate in this driving simulator study. Three participants experienced simulator discomfort and were not able to complete the experiment. Therefore, a total of 44 participants aging from 30 to 48 years (Mean = 37.2, S.D. = 26.1) were included in the experiment. They comprised 21 professional drivers (14 male and 7 female) and 23 nonprofessional drivers (10 male and 13 female). The professional drivers were full-time taxi drivers with an average driving experience of 17.7 years and an average annual driving distance of 94.7 thousand kilometers. The nonprofessional drivers were from different occupations and drove for daily purposes only. Their average driving experience was 9.7 years, with an average annual driving distance of 19.2 thousand kilometers.

3.2. Apparatus. In this study, driving simulation experiment and data collection were carried out using the Beijing Jiaotong University (BJTU) driving simulator (as shown in Figure 3). The high-fidelity driving simulator consists of a one degree-of-freedom motion base platform, an environmental noise simulation system, a digital video replay system, and a curved projection screen providing a 300 degrees front/peripheral field of view at a resolution of 1400×1050 pixels. The full-size vehicle cockpit (Ford Focus) in the simulator is designed in full accordance with a real vehicle and the inside components include the steering wheel, dashboard, brake pedal, throttle, and seats, etc. Meanwhile, it also provides a set of software programs for driving scenario design, virtual traffic environment simulation, virtual road design, and scenario presentation. The sampling frequency of the driving data was 60 Hz.

3.3. Scenario Design. The experiment was a 3 (crossing type) × 5 (FLTT) × 2 (foggy condition) within-subjects repeated-measures design. The three crossing types considered the design of the signs and pavement markings for grade crossings and the presence or absence of two-stage warning. Detailed explanations of the three crossing types are:

(i) Baseline: conventional design of signs and pavement markings for grade crossing in China;

(ii) PSM: the proposed design of signs and pavement markings for grade crossing without warning:

(iii) PSM + W: the proposed design of signs and pavement markings for grade crossing with warning.

FLTT depended on the time of the vehicle arriving at the stop line. Five kinds of FLTT that varied from 2 s to 6 s with 1 s

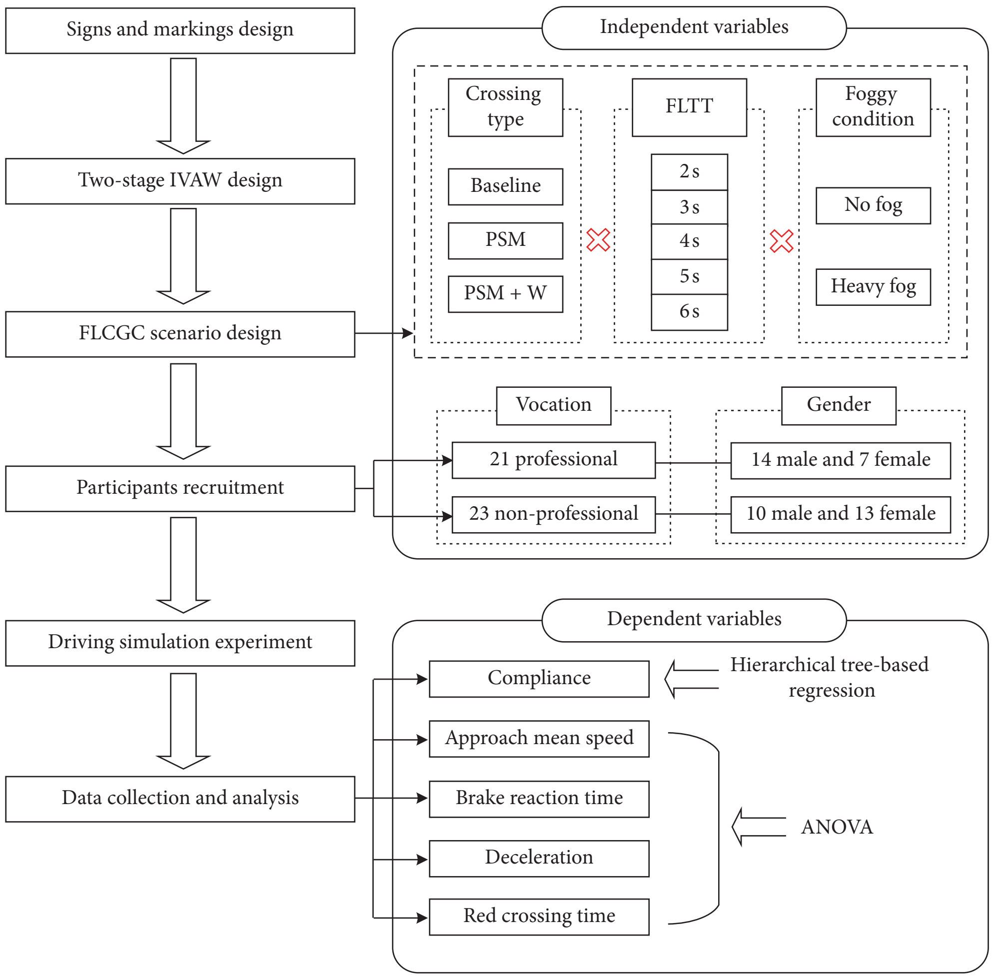


Figure 2: Research framework.

(a) (b)

Figure 3: Illustration of BJTU driving simulator system. (a) Driving simulator; (b) monitoring and controlling systems.

interval were designed in this study. In addition, two foggy conditions including clear and heavy fog were considered to test the effect of PSM and IVAW on drivers' crossing behavior under different foggy conditions. The visibility in heavy fog scenario was 50 m. Thus, a total of 30 different types of experimental scenarios were performed in this study.

The road designed in this experiment was a two-lane, two-way road with lane width of 3.5 m per lane and the speed limit was 70 km/h. All grade crossings were evenly distributed on the road, with each two of them connected by an 800 m straight road segment. The flashing-light signal was activated when the time for the vehicle to arrive at the stop line met the FLTT. Once activated, the red light started flashing at a rate of 60 Hz, accompanied by an audible warning beep (60 dB) ringing at a rate of 60 Hz. The signal duration was 15 s.

The baseline grade crossing followed Chinese design standards and required signage are displayed in Figure 4(a).

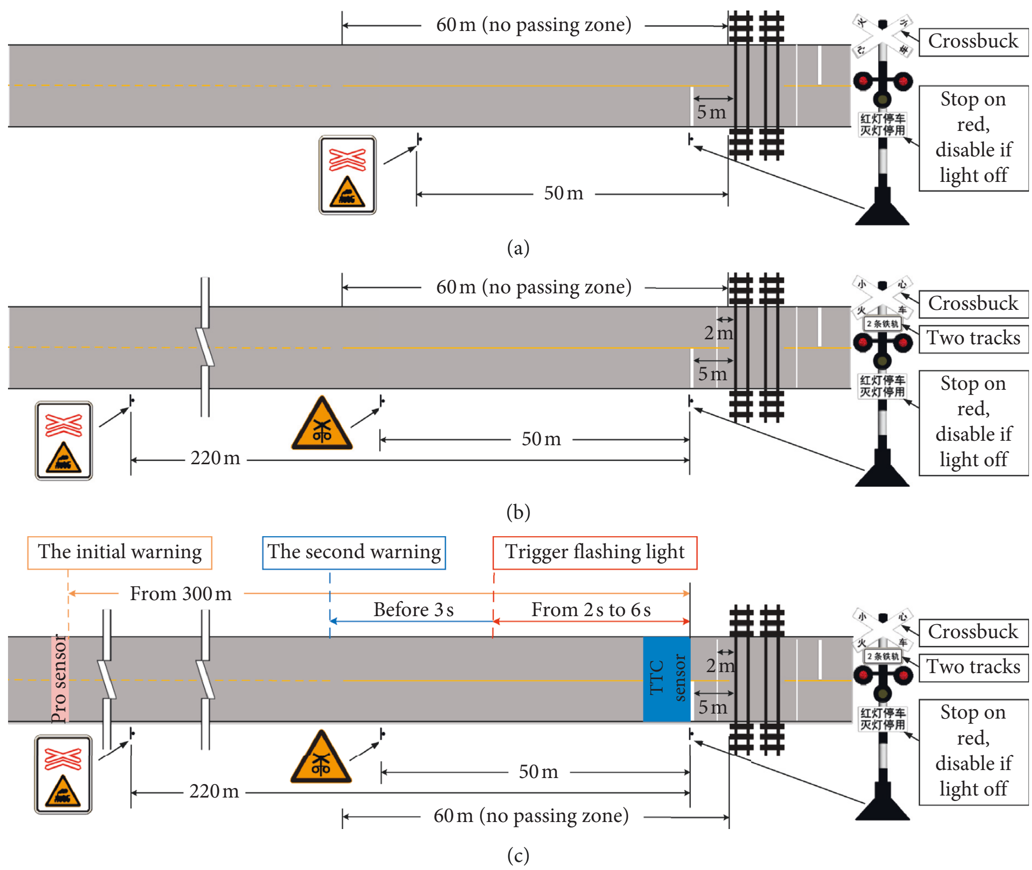


Figure 4: Standard and proposed design of signs and pavement markings for grade crossing of China. (a) Standard design of signs and pavement markings for grade crossing of China; (b) proposed design of signs and pavement markings for grade crossing; (c) diagram of the grade crossing with warning.

The stop line and flashing-light signal were placed 5 m in advance of the crossing railway. The flashing-light signal was assembled on the side of the road together with a crossbuck sign and a "STOP ON RED, DISABLE IF LIGHTS OFF" sign. Meanwhile, a nonguarded grade crossing with multiple tracks sign was positioned on the right side of the road 50 m prior to the railway. The proposed design of traffic control devices for grade crossing was adjusted based on the baseline design (Figure 4(b)). For the flashing lights, a supplemental number of tracks plaque was mounted below the crossbuck sign. DEMs (dynamic envelope markings) were recommended to place on the road 2 m in advance and parallel to the railway. Nonguarded grade crossing with multiple tracks signs were moved to 220 m away from the stop line. In addition, a flashing-light ahead sign was installed 50 m in front of the crossing to provide information to drivers regarding whether they should prepare to stop or go through.

The IVAW triggered verbal cautions: "Flashing lights controlled grade crossing at 300 meters ahead, please be careful!" and "The flashing lights are about to turn red, please slow down!." The initial warning was released when the vehicle was 300 m away from the stop line, and the second was released at 3 s prior to the flashing lights activation, as shown in Figure 4(c).

In this study, two sets of experimental driving routes were designed to test participants' driving performances during the process of approaching grade crossings. One route composed of eight baseline grade crossings and it was 6.4 km in length. In order to minimize drivers' adaptability, memorability, and predictive probability to the repeated tests, five grade crossings with different FLTT were randomly selected as the test grade crossings. The other two grade crossing types were grouped together. The route consisted of fourteen grade crossings designed according to the recommended signs and pavement markings, and the length was 11.2 km. Ten test grade crossings (2 (PSM and PSM + W) × 5 FLTT) were randomly selected from the route. Then, the test crossings of each route were randomly sorted to form three sequences of FLTT. The route of each driver for each driving was randomly selected, so that each driver experienced thirty test grade crossings in different orders.

3.4. Procedure. All participants were briefed about the experiment upon their arrivals. Before formal experiment, all participants were given at least 5 min of training so that they could familiarize with the virtual driving environment and the simulated driving operation. Participants were instructed to practice accelerating and braking gently and to practice maintaining the speed and steering wheel.

Before the experiment, each participant was asked to sign an informed consent form and fill out demographics and general driving questionnaires. In the formal test, they were required to drive and behave as they normally would. The participants were also notified that they could quit the experiment at any time in case of motion sickness or any kind of discomfort. Then, participants drove each scenario under two foggy conditions (clear and heavy fog) in a random sequence to counterbalance the order effect. Each of them was given a break between the tests. One session lasted approximately 1 h for each participant and a compensation of 200 Chinese RMB (about 30 U.S. dollars) was provided for their successful completion.

3.5. Data Analysis. As Figure 5 shows, the factors considered in this study included foggy conditions, gender, vocation, crossing type, and FLTT. Five dependent variables were collected and used to test the effect of PSM and IVAW on drivers' crossing behavior, e.g., compliance or not, approaching mean speed, brake reaction time, red crossing time, and deceleration. Detailed definitions of the above dependent measures were explained as follows:

Compliance or not (Yes = 1; No = 0): the variable represents whether the driver complied with the traffic rules at the grade crossing.

Approaching mean speed: mean speed on approach to the crossing was measured at five distances in front of the crossing: 300 m, 220 m, 100 m, 50 m, and 20 m.

Brake response time (BRT): the time was determined by measuring the time at which the subject vehicle triggered a train crossing "event" (a "warning" or 3 s prior to a "flashing red light") to the time at which the participant first depressed the brake pedal. It was for those approaches where participants did not violate the grade crossing controls.

Deceleration: the change rate of velocity during the period from the time of brake to the time when a maximum brake was reached. It was for those approaches where participants did not violate the grade crossing controls.

Red crossing time (RCT): the time was measured from the time at which the flashing light was activated to the time at which the subject vehicle arrived at the stop line. It reflects the severity of the driver's violation. It was for those approaches where participants violated the grade crossing controls.

The compliance variable was analyzed using hierarchical tree-based regression. The specifications for tree construction include: CHAID algorithm was applied; the maximum tree depth was set as 3 levels; and the significance values for splitting nodes and merging categories were set as 0.05. The minimum number of cases for parent nodes was set as 100 and the minimum number of cases for child nodes was set as 50. Other measures of driving performance were analyzed using ANOVA and used an α-level of 0.05 to determine statistical significance. All analyses were carried out using IBM SPSS Statistics 22.

4. Results

4.1. Compliance. Table 1 lists compliance rates with different factors, including foggy condition, gender, vocation, crossing type, and FLTT. Results of hierarchical tree-based regression are shown in Figure 6. The final tree structure for compliance involved three splitting variables, including gender, crossing type, and FLTT. It means that the aforementioned three variables significantly influenced drivers' compliance, among which FLTT was the most important factor, followed by gender and crossing type. No statistically significant effect of vocation and foggy conditions was found on drivers' compliance.

As shown in Figure 6, the tree contains three levels. In the first level, the compliance (Node 0) was divided into three child nodes (Node 1–3) according to FLTT. In the second level, Node 1 was divided into two child nodes (Node 4-5) by gender, whereas Node 2 and Node 3 were both divided into two child nodes (Nodes 6-7 and Nodes 8-9, respectively) by crossing type. In the third level, Node 4 and Node 5 were divided into two child nodes (Nodes 10-11 and Nodes 12-13) by crossing type. The detailed characteristics could be identified as follows:

In the first level: it was found that FLTT was the most important influencing factor on compliance. For earlier FLTT (4 s, 90.2%; 5 s, 93.6%; 6 s, 93.9%), 92.6% of drivers complied with the rules, which was much higher than the proportion of drivers under the 2 s (34.5%) and 3 s (75.0%) conditions.

In the second level: in the condition of earlier FLTT (4–6 s), gender was the most influencing factor for compliance. 96.7% of female drivers chose to comply with the rules, which was 7.6% higher than the proportion of male drivers. However, for the later FLTTs, e.g., 2 s and 3 s, crossing type was the significant factor among all the factors and no statistically significant effect of gender was found on drivers' compliance. The baseline and PSM were classified into the same subgroup, which means that drivers tended to make the same choice of whether to comply with the rules. The interaction effect of crossing type and FLTT can be more intuitively observed in Figure 7. When the FLTT was 2 s, the compliance rate of PSM + W crossings (65.9%) was found to be significantly higher than that of PSM crossings and baseline (12.5%). When the FLTT was 3 s, 94.3% of drivers who drove in PSM + W scenarios chose to comply with the rules, which was much higher than drivers in baseline and PSM scenarios (65.3%).

In the third level: when the FLTT varied from 4 s to 6 s, both male and female drivers' compliance rates were significantly influenced by crossing type. For female drivers, the baseline and PSM were classified into the same subgroup which means that female drivers tended to make the same choice of whether to comply with the rules. 95% of female drivers tended to comply with the rules in the condition of baseline and PSM, whereas the compliance rate of female drivers in the condition of

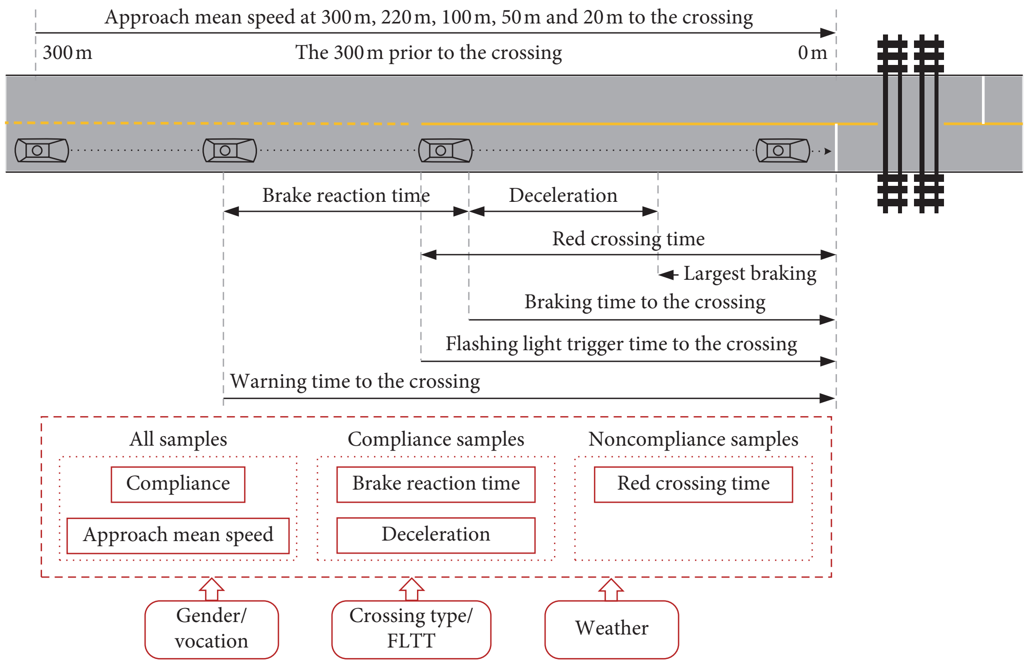


Figure 5: Dependent and independent variables in this study.

Table 1: Basic description for compliance rates.

Effect	Classification	Yes		No		Total
		Count	N%	Count	N%	Count
Foggy condition	Clear	502	76.1	158	23.9	660
	Fog	520	78.8	140	21.2	660
Gender	Male	538	74.7	182	25.3	720
	Female	484	80.7	116	19.3	600
Vocation	P	478	75.9	152	24.1	630
	NP	544	78.8	146	21.2	690
Crossing type	Baseline	307	69.8	133	30.2	440
	PSM	309	70.2	131	29.8	440
	PSM + W	406	92.3	34	7.7	440
FLTT (s)	2	91	34.5	173	65.5	264
	3	198	75.0	66	25.0	264
	4	238	90.2	26	9.8	264
	5	247	93.6	17	6.4	264
	6	248	93.9	16	6.1	264
Total		1022	77.4	298	22.6	1320

PSM + W reached 100%. For male drivers, 91.7% of drivers under the PSM and PSM + W conditions complied with the rules, which was 7.7% higher than those under baseline condition.

4.2. Approaching Mean Speed. For drivers who complied with the rules, their speed profiles while approaching different types of grade crossings were calculated. Figure 8 presents the approaching mean speed (AMS) profiles for different FLTTs. Each subfigure provides the mean speed of subject vehicle from 400 m in front of a crossing to 10 m behind it (the stop line is considered as 0 m from the grade crossing). It can be found that for all three types of crossings, drivers almost kept a constant approaching speed. In baseline, drivers approached the crossing at a higher speed until they observed the warning sign at 45 m distance and then started to slow down. However, drivers started to slow down earlier at PSM crossings than baseline. As the warning signs were 220 m ahead of crossings, drivers approached the crossing at a lower speed. At PSM + W crossings, drivers received a voice message when they were 300 m in front of the crossing, which prompted them to slow down earlier and approach at lower speeds compared with the other conditions.

Effects of foggy condition, gender, vocation, crossing type, and FLTT on drivers' approaching speed were further analyzed at five distances of interest: 300 m to the crossing

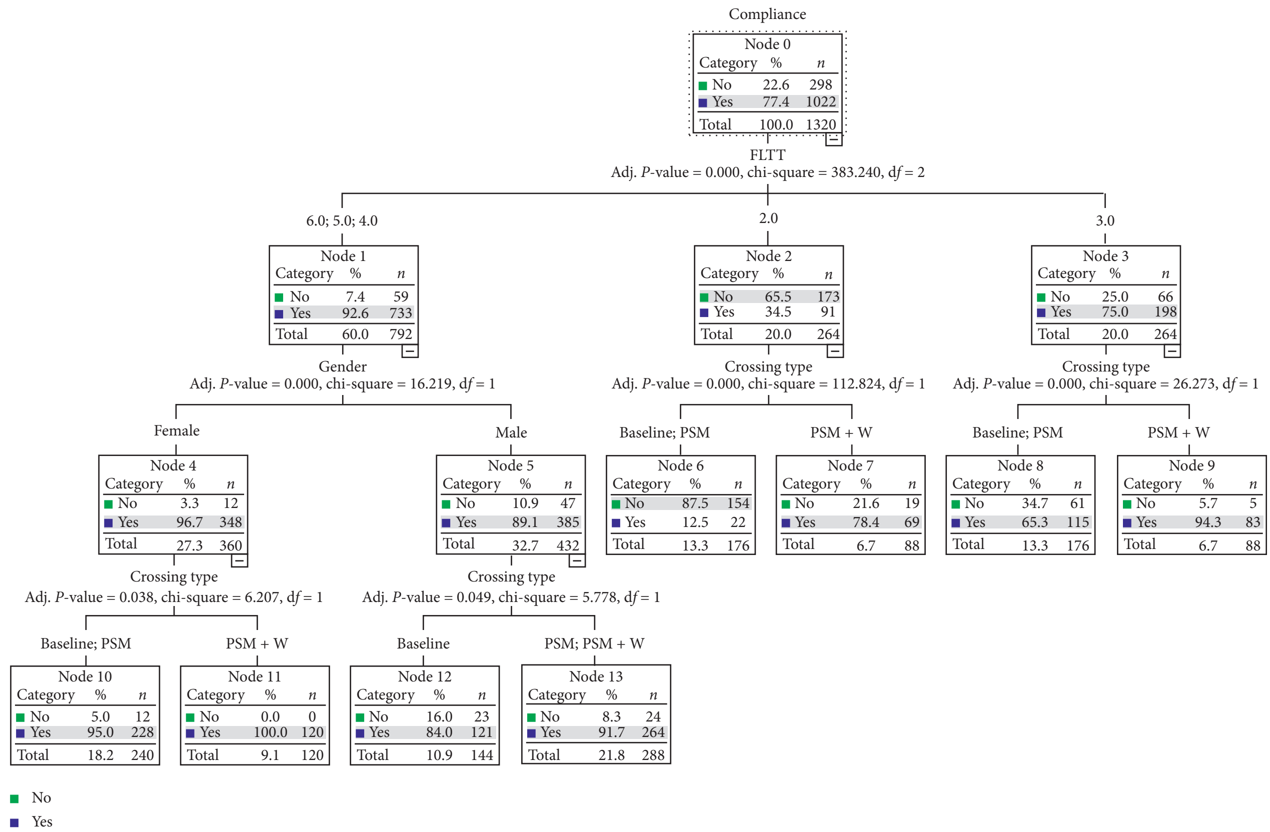


Figure 6: Hierarchical tree-based regression (HTBR) model: predicting drivers' compliance within different categories of factors.

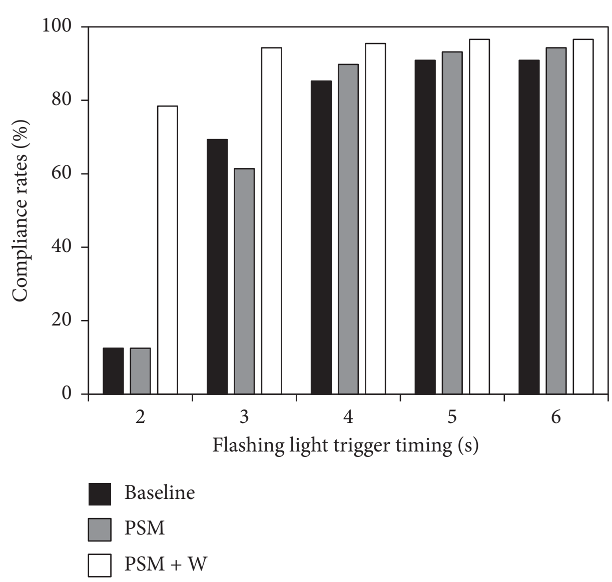


Figure 7: Proportions of drivers who compliant after the flashing light triggered.

(the initial warning occurred at this position under PSM + W condition), 220 m to the crossings (a nonguarded grade crossing with multiple tracks sign was adopted under PSM and PSM + W conditions), 100 m to the crossing, 50 m to the crossing (a flashing-light ahead sign was adopted under PSM and PSM + W conditions), and 20 m to the crossing. Table 2 shows the mean speed within different categories under different factors conditions, and Table 3 summarizes the ANOVA results for these measures.

At 300 m to the grade crossing, mean speed was significantly affected by foggy conditions ($F = 187.055$, $P < 0.001$) and gender ($F = 5.583$, $P = 0.018$). The mean speed in no fog was significantly higher than that in heavy fog and male drivers' mean speed was higher than that of female drivers. However, no significant effect was found for all the other factors on speed at 300 m to the crossing.

ANOVA analysis (as shown in Table 3) showed that drivers' approaching speed at 220 m to the crossing was significantly affected by foggy conditions ($F = 179.128$, $P < 0.001$) and crossing type ($F = 35.005$, $P < 0.001$). Similar to the mean speed at 300 m to the crossing, the mean speed at 220 m in no fog was also significantly higher than that in heavy fog. As for three kinds of crossing types, smallest speed could be found at PSM + W crossings, while no obvious difference between PSM crossings and baseline was observed.

At 100 m to the grade crossing, crossing type ($F = 85.097$, $P < 0.001$), foggy conditions ($F = 11.610$, $P = 0.001$), and their interaction effect ($F = 3.238$, $P = 0.040$) had significant influence on the mean speed. As Figure 9 illustrated, drivers tended to keep a lower speed at 100 m to PSM crossings than in baseline. The mean speed at PSM + W crossings was lowest among all the three crossing types. Moreover, the mean speed in no fog was larger than that in heavy fog

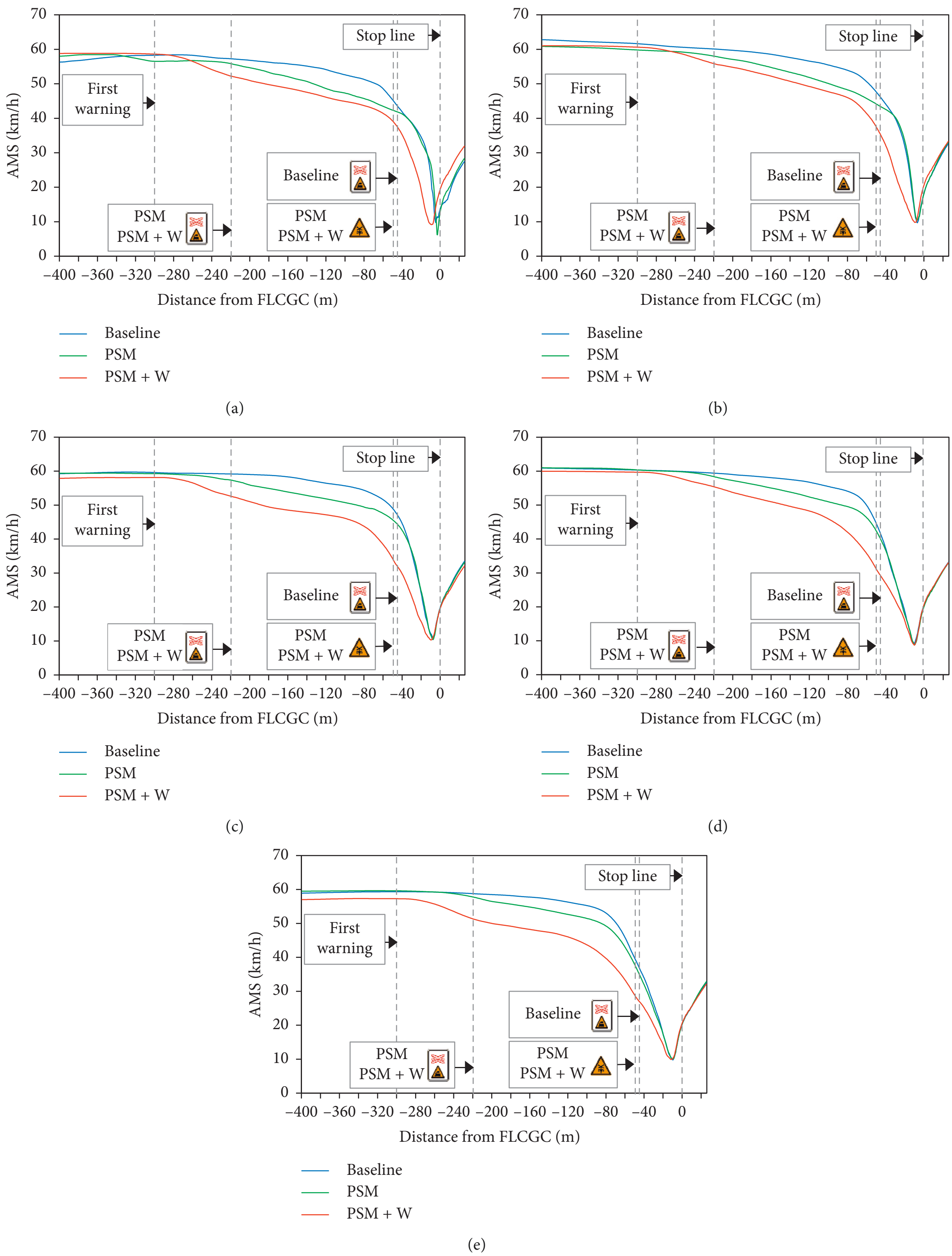


FIGURE 8: Approaching mean speed profiles for different flashing light trigger timings. (a) The FLTT was 2 s; (b) the FLTT was 3 s; (c) the FLTT was 4 s; (d) the FLTT was 5 s; (e) the FLTT was 6 s.

under both PSM and PSM + W conditions, whereas for baseline, no difference was found between clear and heavy fog conditions.

At 50 m to the grade crossing, foggy conditions exhibited a significant impact on mean speed ($F = 5.080$, $P = 0.024$) and drivers maintained a higher speed in heavy fog than that

Table 2: Mean speed within different categories of factors.

Effect	Classification	Parameter	Speed 300	Speed 220	Speed 100	Speed 50	Speed 20
Foggy condition	Clear	Mean	63.41	60.95	52.00	41.00	25.04
		S.D.	67.35	77.72	116.85	165.93	262.75
	Fog	Mean	55.94	53.36	50.07	42.44	25.53
		S.D.	130.66	147.83	139.57	153.25	208.01
Gender	Male	Mean	60.19	57.55	51.34	41.28	24.07
		S.D.	124.19	139.93	145.29	178.89	261.02
	Female	Mean	59.00	56.62	50.66	42.25	26.75
		S.D.	99.22	112.07	109.71	136.93	200.35
Vocation	P	Mean	59.57	56.88	51.19	41.65	24.86
		S.D.	121.40	138.89	129.91	177.84	276.51
	NP	Mean	59.71	57.35	50.88	41.79	25.68
		S.D.	105.69	116.96	128.57	143.81	197.23
Crossing type	Baseline	Mean	59.86	59.14	55.30	46.18	28.82
		S.D.	114.47	108.86	113.43	149.87	250.92
	PSM	Mean	60.08	58.43	51.78	46.18	29.56
		S.D.	108.58	118.27	128.76	155.25	273.12
	PSM + W	Mean	58.99	53.81	46.01	34.62	17.48
		S.D.	116.13	138.87	101.77	97.94	90.29
FLTT (s)	2	Mean	59.34	56.98	50.92	45.40	36.98
		S.D.	129.46	136.37	137.35	161.25	292.17
	3	Mean	60.64	58.03	51.48	44.23	30.54
		S.D.	105.66	118.53	123.11	156.10	235.84
	4	Mean	59.02	56.39	51.02	43.15	23.09
		S.D.	111.92	128.76	134.80	175.54	166.92
	5	Mean	60.16	57.83	51.12	39.77	18.43
		S.D.	100.65	111.68	120.38	129.66	100.78
	6	Mean	59.07	56.40	50.61	36.08	17.40
		S.D.	117.49	141.11	131.59	121.83	103.77

Table 3: ANOVA summary table of the effect of factors on approaching mean speed.

Source	d.f.	*F*-ratio				
		Speed 300	Speed 220	Speed 100	Speed 50	Speed 20
Foggy condition	1	187.055*	179.128*	11.610*	5.080*	0.458
Gender	1	5.583*	3.768	1.141	2.537	14.530*
Vocation	1	0.485	1.340	0.090	0.020	0.094
Crossing type	2	1.578	35.005*	85.097*	138.235*	136.307*
FLTT	4	1.385	1.483	0.231	30.888*	124.173*
Crossing type × foggy condition	2	1.382	0.749	3.238*	1.520	0.171
Crossing type × gender	2	0.540	0.569	0.058	0.681	0.237
Crossing type × vocation	2	0.576	1.036	0.043	0.180	1.698
FLTT × crossing type	8	0.304	0.739	0.578	1.754	14.872*
FLTT × foggy condition	4	0.842	1.196	0.546	2.262	7.451*
FLTT × gender	4	0.179	0.213	0.095	0.521	0.874
FLTT × vocation	4	0.043	0.207	0.332	0.573	0.196

*Significant at the 0.05 level.

in no fog (42.44 km/h vs. 41.00 km/h). FLTT ($F = 30.888$, $P < 0.001$) and crossing type ($F = 138.235$, $P < 0.001$) were also significant factors of mean speed. Drivers' mean speed gradually decreased with the increase of FLTT. For three crossings, significant speed reduction could be found at PSM + W crossings, whereas no obvious difference between PSM crossings and baseline was found.

Finally, ANOVA analysis showed that at 20 m to the crossing, gender had a significant impact on mean speed ($F = 14.530$, $P < 0.001$) and male drivers kept a smaller mean speed than female drivers. Furthermore, the mean speed was also significantly affected by crossing type ($F = 136.307$, $P < 0.001$), FLTT ($F = 124.173$, $P < 0.001$), and their interaction ($F = 14.872$, $P < 0.001$). Figure 10 shows drivers' mean speed under different crossing types and foggy conditions in each FLTT condition. Generally, drivers' approaching speed decreased with the increase of FLTT for all crossings. The mean approaching speed at PSM + W crossing was significantly lower than that of PSM crossing and baseline. With the increase of FLTT, the difference of speed between

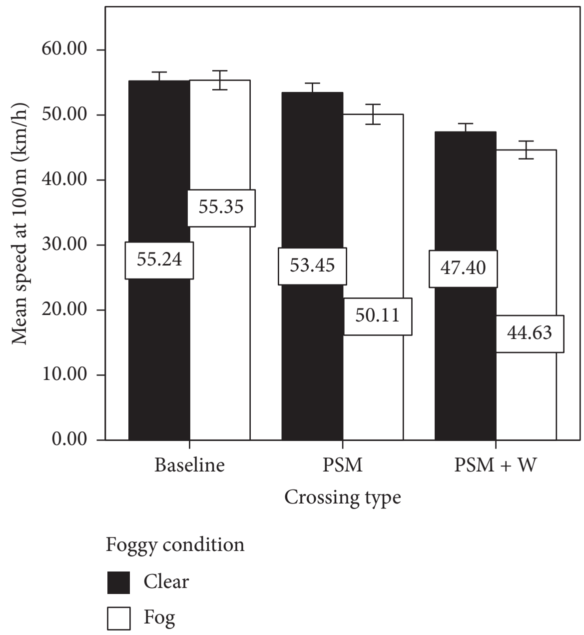


Figure 9: Mean speed at 100 m to the crossing for the interaction between crossing type and foggy condition.

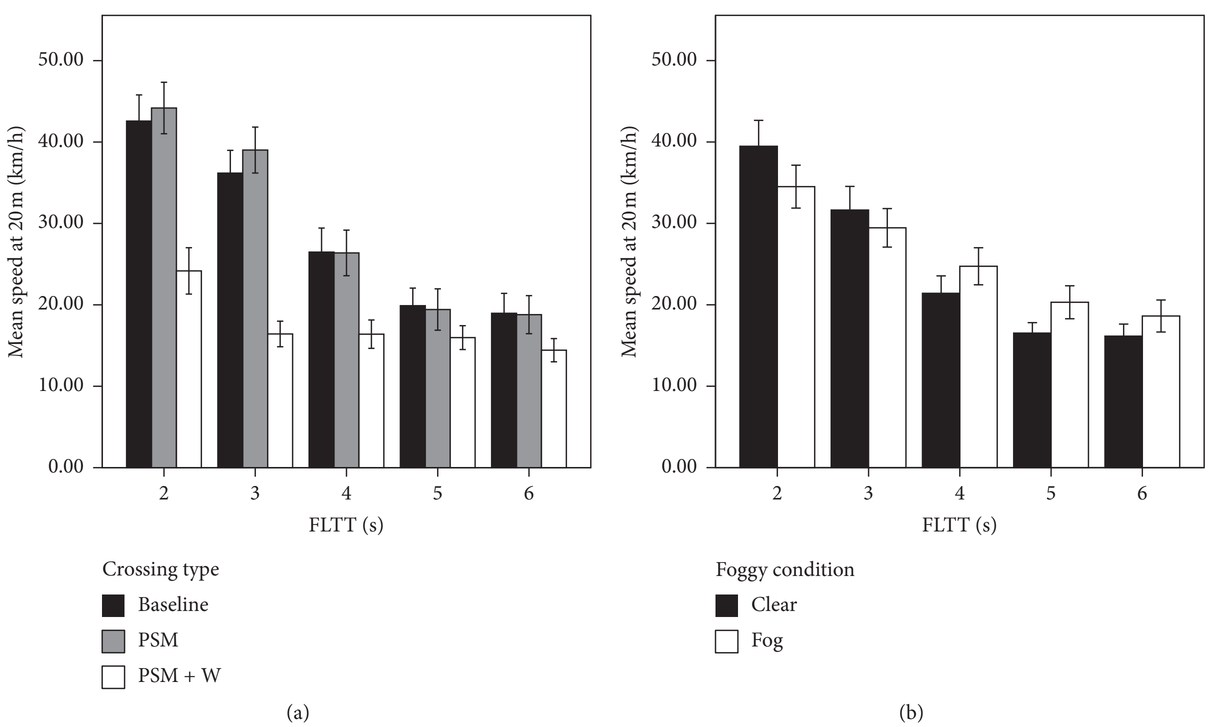


Figure 10: Mean speed at 20 m to the crossing under different FLTTs. (a) The interaction effect between FLTT and crossing type; (b) the interaction effect between FLTT and foggy condition.

PSM + W crossing and the other two crossing types became smaller. For foggy conditions (as shown in Figure 10(b)), different patterns could be found for different FLTTs. Generally, when FLTT was late, e.g., 2 s and 3 s, drivers maintained a larger speed in clear weather than in heavy fog. However, for early FLTTs, the results were quite opposite as drivers' mean speed was larger in heavy fog than in clear weather.

4.3. Brake Response Time. Table 4 lists driving performance with different factors, including foggy condition, gender, vocation, crossing types, and FLTTs. According to the ANOVA results (Table 5), foggy conditions ($F = 35.269$, $P < 0.001$), gender ($F = 6.625$, $P = 0.001$), crossing type ($F = 305.019$, $P < 0.001$), and FLTT ($F = 25.587$, $P < 0.001$) all had significant impacts on BRT. Regardless of the crossings types, drivers' BRTs in clear weather were smaller than that in heavy fog and male drivers tended to brake earlier than female drivers. However, no statistically significant difference was found between professional and nonprofessional drivers. For crossing types, drivers braked earlier at PSM crossing and PSM + W crossing compared to baseline, especially at PSM + W crossing. For different FLTTs, drivers' BRTs were larger in the condition of earlier FLTTs.

Moreover, three significant interaction effects were found, e.g., crossing type × foggy conditions ($F = 7.037$, $P = 0.001$), crossing type × gender ($F = 4.533$, $P = 0.011$), and FLTT × foggy conditions ($F = 4.554$, $P = 0.001$). Figure 11 presents the mean BRT for different combinations of crossing types and gender. It could be noted that male and female drivers had significant differences in BRT at baseline crossings. However, the gender difference in BRT was degraded when PSM was applied, especially for the PSM + W condition. Figure 12 presents drivers' BRT for different combinations of FLTT and foggy conditions. It could be found that the difference of BRTs between clear and heavy fog became larger as the FLTT increased.

4.4. Deceleration. The ANOVA results for deceleration indicate the significant impacts of foggy condition ($F = 3.924$, $P = 0.048$) and vocation ($F = 8.673$, $P = 0.003$). Drivers' decelerations in clear weather were smaller than that in heavy fog, and professional drivers tended to brake with larger deceleration than nonprofessional drivers. Similar to the BRT, deceleration was also influenced by crossing type ($F = 84.017$, $P < 0.001$), FLTT ($F = 22.208$, $P < 0.001$), and their interaction ($F = 2.341$, $P = 0.017$). According to Table 4, drivers' deceleration in the PSM conditions was slightly reduced compared with the baseline. In the PSM + W condition, the deceleration was further reduced, which demonstrates that warning messages enabled drivers to brake with a more comfortable deceleration with least fluctuations. Figure 13 presents the mean deceleration for different FLTTs. The FLTT varied from 3 s to 6 s and, for the earlier FLTTs, the deceleration gradually reduced as well as the standard deviation. However, the deceleration of the latest FLTT (2 s) was not the largest, because drivers were more likely to go through the crossings and less likely to brake in such situation. When the PSM was used, the deceleration rate was largest for the latest FLTT (2 s), especially for the PSM + W condition, which implies that drivers relying on the IVAW may take an emergent brake.

Moreover, the interaction of crossing type × foggy condition ($F = 5.733$, $P = 0.003$) also illustrated a significant impact on deceleration. Figure 14(a) presents the mean deceleration for different combinations of crossing types and foggy conditions. In no fog, the deceleration for PSM showed no significant differences in comparison to the group of baseline, whereas the deceleration under the PSM + W condition reduced significantly. Differently in heavy fog, the deceleration significantly reduced under both PSM and PSM + W conditions. Moreover, for baseline, drivers' deceleration in fog was much greater than that in clear weather. However, in PSM and PSM + W conditions, the difference of deceleration between fog and clear weather was reduced.

Although gender ($F = 0.215$, $P = 0.643$) did not show significant impact on deceleration, the interaction effect between crossing type and gender ($F = 2.998$, $P = 0.050$) was significant. As illustrated in Figure 14(b), female drivers were more likely to exhibit a larger deceleration than male drivers under the baseline condition. On the contrary, female drivers' deceleration was smaller than that of male drivers at PSM and PSM + W crossings, indicating that male drivers could control the vehicles more smoothly whereas female drivers were more sensitive to the changes in signs and warning messages.

4.5. Red Crossing Time. According to the ANOVA results (Table 5), both gender ($F = 8.918$, $P = 0.003$) and vocation ($F = 4.523$, $P = 0.034$) exhibited significant impacts on RCT. Male drivers' RCTs were significantly longer than female drivers' (5.81 s vs 3.64 s). Similarly, nonprofessional drivers also spent more time during approaching than professional drivers. The main effect of FLTT ($F = 11.706$, $P < 0.001$) and its interaction effect with vocation ($F = 3.912$, $P = 0.004$) on RCTs were also significant. As illustrated in Figure 15, as the FLTT increased, nonprofessional drivers' RCTs increased rapidly, whereas professional drivers' RCTs increased relatively slowly with fewer fluctuations. In this experiment, no clear impact of crossing types ($F = 0.304$, $P = 0.738$) and foggy conditions ($F = 0.352$, $P = 0.553$) on RCTs was found.

5. Discussion

5.1. Influencing Mechanism of PSM and IVAW on Driving Behavior. The study conducted a simulator-based experiment to examine the effects of PSM and IVAW on drivers' driving performances during the process of approaching grade crossings controlled by flashing light. In addition, whether the effects of PSM and IVAW varied with drivers' gender, vocation, and foggy conditions was tested in this study as well.

Generally, users' compliance rate can be used to evaluate system effectiveness in varying safety countermeasures [5, 23]. The hypothesis that PSM is associated with safer driver behavior compared with current signs and markings is not supported by the compliance data. 70.2% of participants successfully stopped at the PSM grade crossing, whereas 69.8% of participants successfully stopped at the baseline grade crossing. The similar proportion of participants who made compliances at both crossings may be due to the similarity in perceptual cues provided by passive traffic control devices. Both signs and marking designs provided drivers with a "soundless" warning of the nonguarded grade crossings in front. For crossing with flashing light but without IVAW, drivers are not informed whether the flashing light is about to turn red. If the flashing light is activated when the vehicle is close to the crossing, drivers may make hasty and incorrect stop/go decisions. At both "soundless" crossings, over one-third of drivers made a violation when the FLTT was 3 s, and the violation rate

Table 4: Mean driving performance within different categories of factors.

Effect	Classification	BRT (s)	Decelerate (m/s/s)	RCT (s)
Foggy condition	Clear	2.17 ± 2.48	2.09 ± 1.49	4.67 ± 20.49
	Fog	2.69 ± 2.53	2.25 ± 1.35	5.28 ± 29.02
Gender	Male	2.33 ± 2.40	2.18 ± 1.43	5.81 ± 27.39
	Female	2.57 ± 2.72	2.17 ± 1.42	3.64 ± 17.67
Vocation	P	2.41 ± 2.54	2.27 ± 1.45	4.73 ± 21.57
	NP	2.47 ± 2.60	2.09 ± 1.39	5.21 ± 27.90
Crossing type	Baseline	3.50 ± 1.80	2.62 ± 1.69	4.88 ± 22.63
	PSM	3.32 ± 1.82	2.37 ± 1.80	4.74 ± 26.29
	PSM + W	1.29 ± 1.01	1.69 ± 0.53	6.16 ± 26.05
FLTT (s)	2	0.97 ± 0.68	2.33 ± 1.10	3.70 ± 22.42
	3	1.87 ± 1.95	2.51 ± 2.05	4.99 ± 18.75
	4	2.48 ± 2.30	2.40 ± 1.92	7.35 ± 18.09
	5	2.70 ± 2.55	1.99 ± 1.00	10.09 ± 31.98
	6	3.10 ± 2.48	1.82 ± 0.71	9.22 ± 8.17
Total		2.44 ± 2.57	2.17 ± 1.42	4.96 ± 24.65

Table 5: Results of ANOVA for dependent measures.

Source	d.f.	*F*-ratio		
		BRT	Deceleration	RCT
Foggy condition	1	35.269*	3.924*	0.352
Gender	1	6.625*	0.215	8.918*
Vocation	1	0.020	8.673*	4.523*
Crossing type	2	305.019*	84.017*	0.304
FLTT	4	25.587*	22.208*	11.706*
Crossing type × foggy condition	2	7.037*	5.733*	0.184
Crossing type × gender	2	4.533*	2.998*	0.388
Crossing type × vocation	2	0.783	0.811	2.977
FLTT × crossing type	8	1.640	2.341*	0.358
FLTT × foggy condition	4	4.554*	1.178	0.632
FLTT × gender	4	1.158	0.490	1.087
FLTT × vocation	4	0.243	0.184	3.912*

*significant at the 0.05 level.

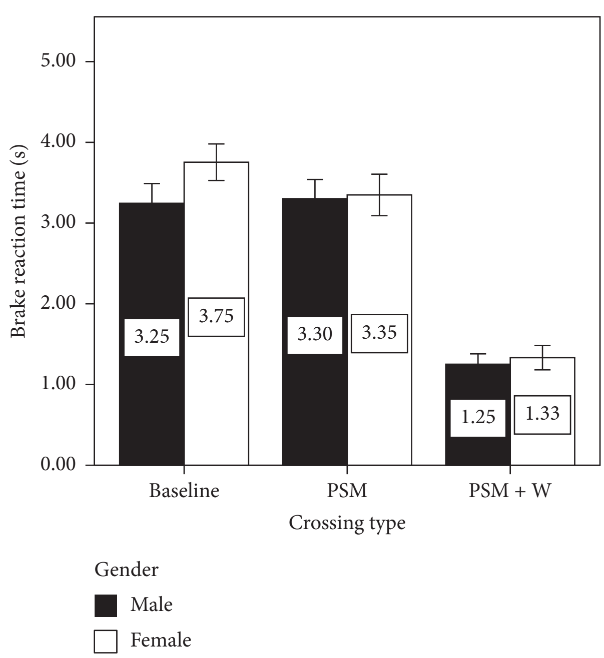


Figure 11: Mean BRT for the interaction between crossing type and gender.

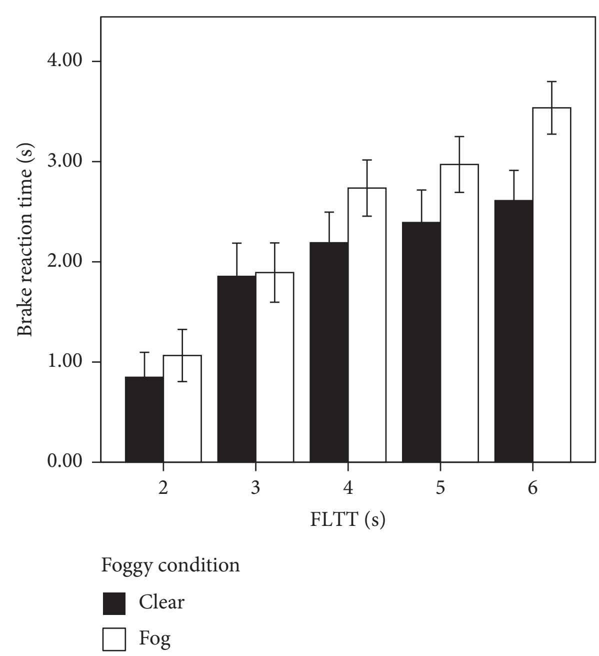
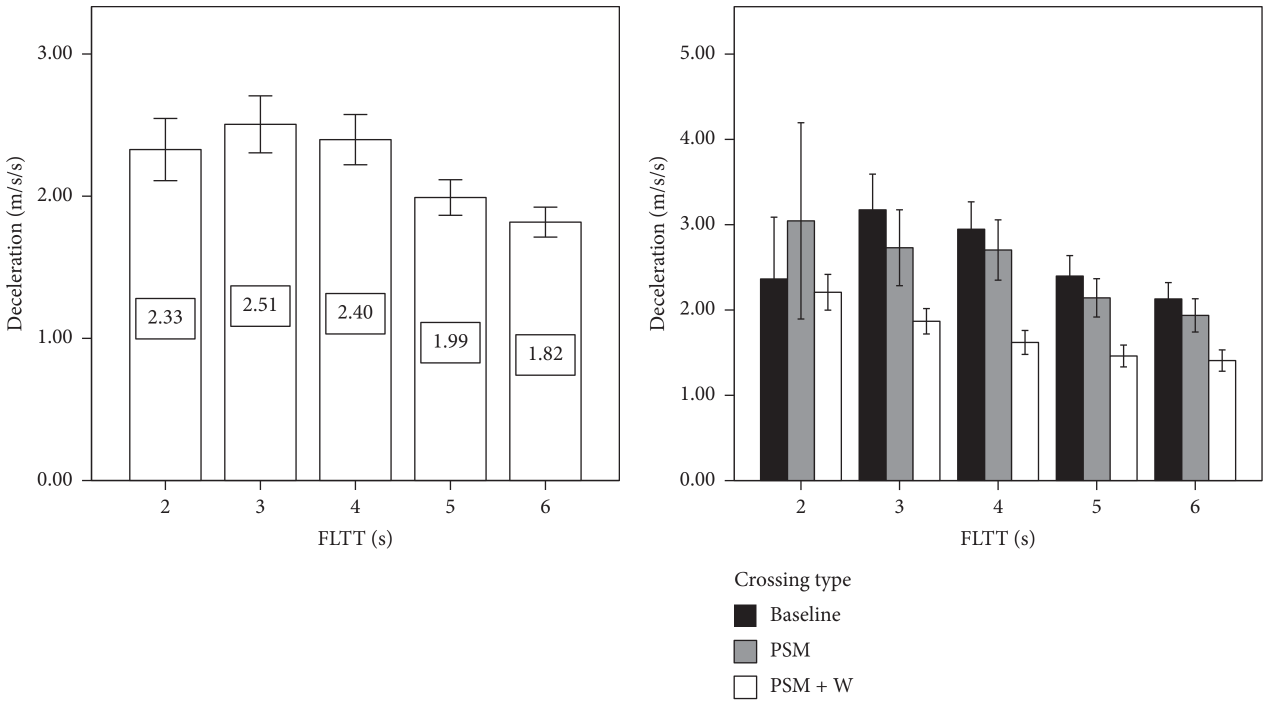
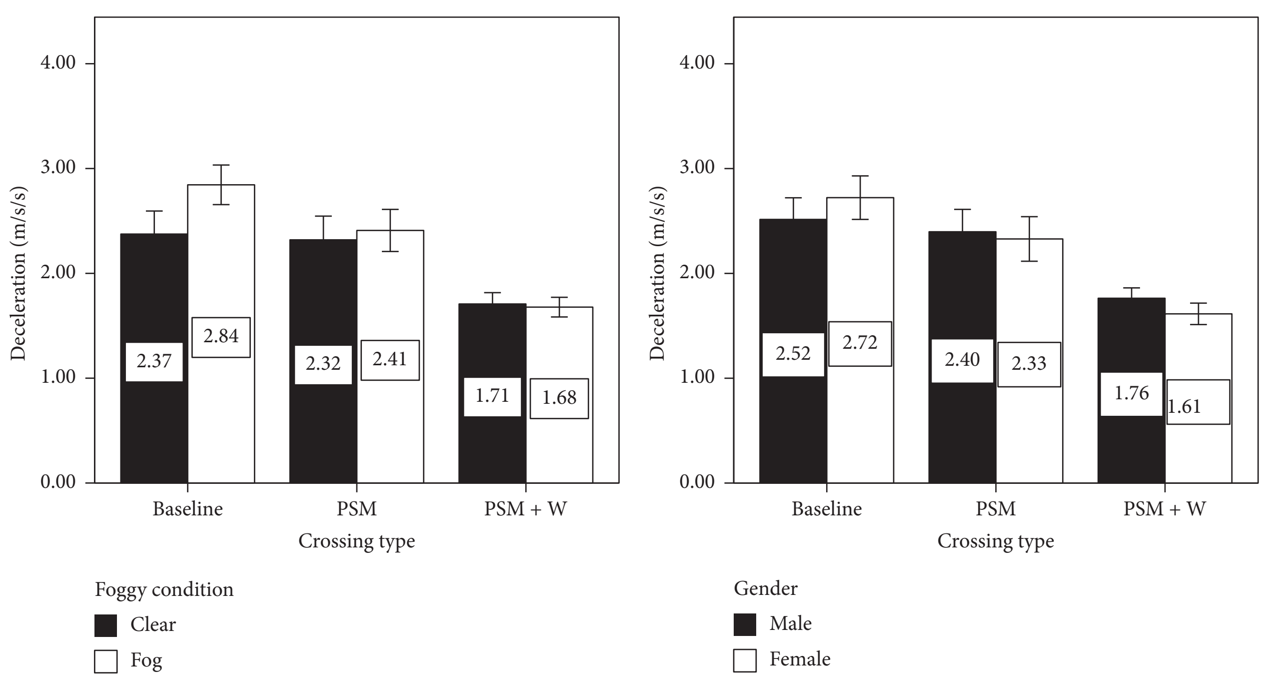


Figure 12: Mean BRT for the interaction between flashing light trigger timings and foggy condition.



(a) (b)

Figure 13: Mean decelerations under different flashing light trigger timing. (a) The main effect of FLTT; (b) the interaction effect between FLTT and crossing type.



(a) (b)

Figure 14: Mean decelerations under different crossing types. (a) The interaction effect between crossing type and foggy condition; (b) the interaction effect between crossing type and gender.

reached 87.5% when the FLTT was 2 s. This result is also supported by the approaching mean speed (AMS) profile of those drivers who chose to violate the flashing lights. Figure 16 illustrates an example and shows a tendency for drivers to reduce speed before subsequently accelerating to pass through the grade crossing. It is possible that some

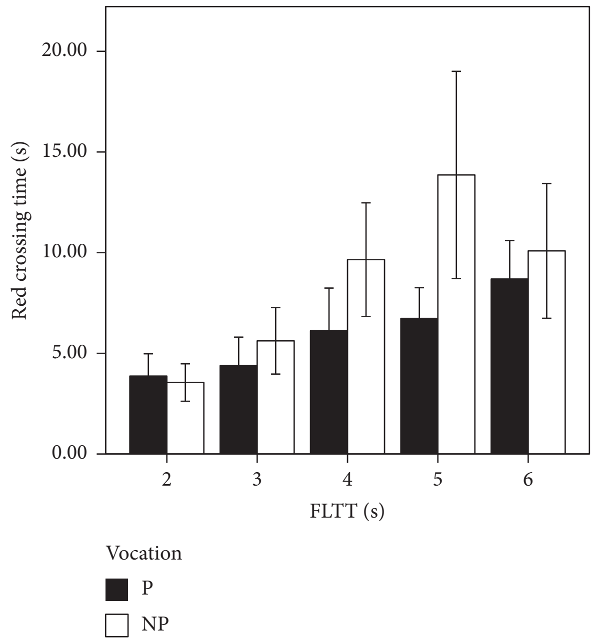


Figure 15: Mean RCT for the interaction between FLTT and vocation.

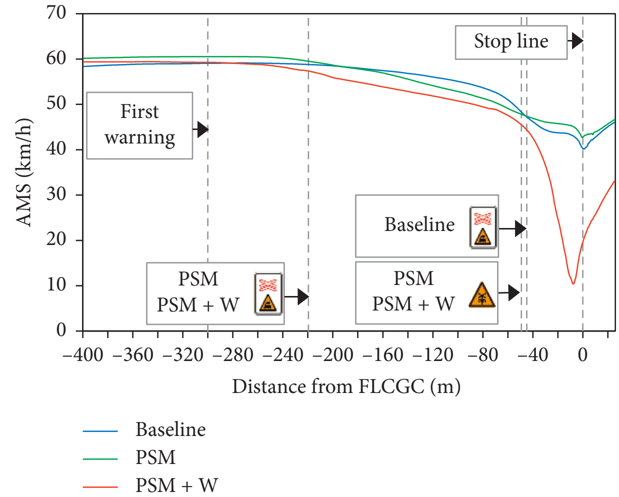


Figure 16: Approaching mean speed profiles of violation when the FLTT was 2 s.

drivers crossed the grade crossings because they felt it hard to stop, or they did not see a train coming [4, 51]. As expected, the additional IVAW resulted in a higher compliance rate (92.3%) as compared to the conventional signage intervention. In particular, the IVAW sharply reduced the number of participants deciding to go through the crossing at late FLTTs.

Although the system seems to affect the compliance rate, drivers' speed change patterns should also be investigated to better understand the performance of the system. The mean speed reduction on approach to a crossing can highlight the safety benefit and it has been investigated in various studies [5, 52, 53]. In this study, it is found that the speed patterns at different types of crossings were significantly different. Compared to baseline crossings, PSM led to an earlier slowing down before 220 meters to the crossings. The speed reduction from 220 meters to 50 meters can possibly be explained by the placement of nonguarded grade crossing signs and grade crossing signal ahead signs. The finding confirms that drivers would pay attention to signs and take corresponding action when approaching the grade crossings. However, the speed profiles of both PSM crossings and baseline were highly coincident as drivers got closer to the crossings. It is likely that the presence of advance warning signs merely affected the perception of crossing, instead of drivers' stop-go decisions. After receiving the first-stage warning information at PSM + W crossings, drivers had obvious deceleration behavior. Meanwhile, compared with the other two types of grade crossings, the brake for stop appeared earlier at PSM + W crossings and the whole deceleration process was smoother owing to the second-stage warning.

In addition, the safety improvement of PSM and PSM + W is supported by shorter BRT and smaller deceleration (see Figure 17). Overall, the BRT and deceleration at PSM crossings were slightly smaller than that of baseline. Specifically, drivers under the PSM + W condition responded to the events earlier with least fluctuations. Drivers' BRT was longer and their deceleration was smaller in the condition of earlier FLTTs. This indicates that drivers would slow down in advance to deal with the change of flashing light when they were closer to the grade crossing and then make well-prepared actions. Thus, they had sufficient time to move to the brake pedal and pressed slowly and continuously until stopping in front of the stop line. Moreover, the deceleration of the latest FLTT (2 s) was not the largest, because drivers were more likely to go through the crossings. Thus, the mean speed at 20 m to the PSM crossings was higher than that of baseline.

5.2. Applicability of the System in Foggy Weather. Reduced visibility in fog increases the risk of collision to some extent, and most drivers are likely to perform safety-related adaptations [54, 55]. In this study, the heavy fog resulted in a late response to the change of flashing light at baseline crossings. Especially at earlier FLTTs, the BRT in heavy fog condition was obviously longer than that in no fog condition. It was hard for drivers to detect and respond to the flashing light in fog until the vehicle was 50 m to the crossing. In such case, drivers had to take a greater deceleration, which may increase their involvement in rear-end crash. Moving the warnings upstream in foggy weather could enhance drivers' situation awareness in advance, and this is supported by a lower approaching speed and deceleration and a shorter reaction time. In no fog, the PSM did not show benefit in improving reaction time as drivers can easily detect the crossings. When the IVAW was applied, the reaction time and deceleration in both foggy conditions were greatly reduced, suggesting the advantages of IVAW over PSM and baseline. The finding shows that the system can compensate for the insufficient visibility in fog. Additionally, the study shows that foggy conditions have no significant

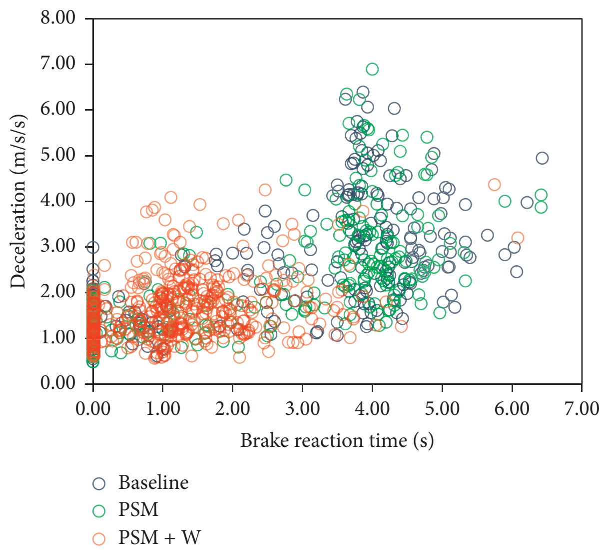


Figure 17: Brake reaction time and deceleration under different crossing types.

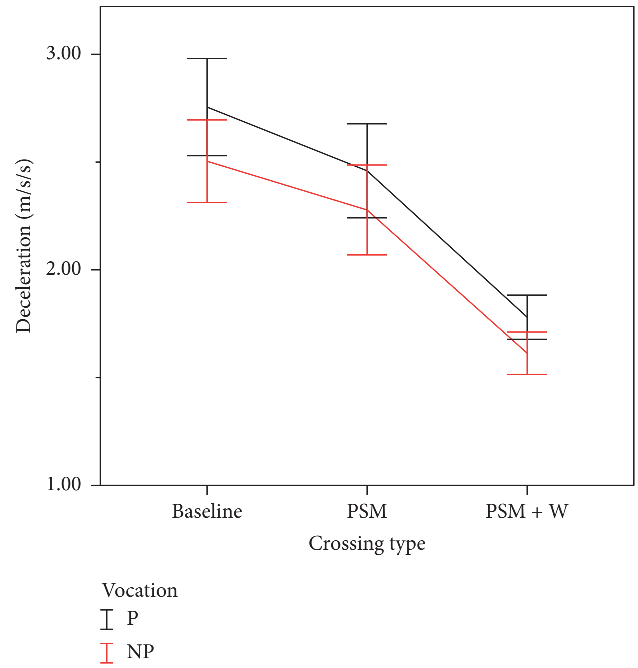


Figure 18: Deceleration under different crossing types × vocation.

impact on the compliance rate. The result implies that the possibility for intentional violation should be higher than the unintentional violation in the study, as the visibility condition in fog is more likely to increase unintentional violation rate.

5.3. Adaptability of Drivers with Different Characteristics to the System. Drivers' characteristics played an important role in perception, decision-making, and reaction during the process of approaching grade crossings. For example, compared with female drivers, male drivers were more likely to violate the flashing light, which is consistent with the previous observations [45, 56]. Especially in the case of earlier FLTTs, gender was a key demographic variable influencing compliance rate, and thus it was preferentially used to examine the effectiveness of the system. Female drivers were not sensitive to the change of signs and markings design, but the additional IVAW could increase the compliance rate to 100%. Furthermore, our findings indicated that compared with female drivers, male drivers tended to brake earlier, but the application of two countermeasures narrowed the gap of BRTs between different genders. On the other hand, the RCT of male drivers was 2.2 s (59.6%) longer than that of female drivers, which implies that male drivers tended to be more cautious and conservative in dealing with dangerous situations. However, no gender effect was observed on the approaching speed and deceleration in this study, and this is consistent with previous studies [57]. It is speculated that male drivers and female drivers are similar in vehicle control abilities when approaching a grade crossing.

As for vocation, professional drivers were more likely to cross the crossing with short RCTs than nonprofessional drivers. Especially when the FLTT increased, professional drivers tended to act faster and thus had a smaller risk of vehicle-train crash. It is confirmed that professional drivers have more driving experience and are more skillful in crash avoidance [58, 59]. However, for those professional drivers who made stop decisions, they had more abrupt deceleration than nonprofessional drivers (as illustrated in Figure 18). A possible explanation is that those drivers had actually prepared to accelerate to pass through the crossings before light flashing. The two countermeasures investigated in the study did not discriminate the effect on deceleration of professional and nonprofessional drivers. Although vocation did not have significant impacts on the compliance rate and approaching speed, it was found that nonprofessional drivers drove slightly higher speeds than professional drivers when approaching the grade crossings. A similar finding has been reported in the prior study, with nonprofessional drivers driving faster than professional drivers when approaching the intersections [42]. In the baseline condition, professional drivers (35.24%) have a larger violation rate than nonprofessional drivers (25.65%). Similarly, previous studies have reported that professional drivers were more inclined to cross the intersection during the yellow indication period because they had a higher economic pressure and need to save time while driving [57, 60]. Many professional drivers have formed the habit of accelerating during the yellow light interval [61]. Thus, when they encountered a flashing light change at grade crossings, they were less willing to wait for the train. The phenomenon was most evident when the FLTT was 4 s. In this case, the compliance rate of professional drivers (86.51%) was 6.97% lower than that of nonprofessional drivers (93.48%). The PSM and PSM + W narrowed the difference in compliance rates between different vocations. Furthermore, there was no difference between professional drivers and nonprofessional drivers on BRT. It implied that drivers' perceptual response largely depend on the drivers' physiological character, instead of the drivers' skill and personal habit.

6. Conclusion

The driving simulator experiment illustrates the effects of crossing types on driver behavior in a range of FLTTs. The study contributes to a better understanding of the effectiveness of conventional devices and advanced warning technology used at grade crossings. The results suggest that PSM could offer limited safety benefits. To some extent, the PSM resulted in lower AMS, shorter BRT, smaller deceleration, and shorter RCT, whereas no evident difference in compliance rate was observed compared with baseline. When the IVAW was in use, the compliance rate was improved remarkably, especially under late FLTTs (i.e., 2 s, 3 s). In addition, the ASM, BRT, and deceleration were substantially reduced with small fluctuations. In general, the positive effect of PSM was most obvious when the FLTT was 3 s, whereas the IVAW enhanced driving performances under various conditions. The study reveals that the countermeasure combining PSM and IVAW can be developed as a safety tool for assisting in drivers' stop/go decision and safe driving at grade crossings.

The study also demonstrates the negative impact of foggy weather on driving behavior, though the impact could be remedied by both PSM and IVAW. It could be expected that the intervention system should have comparable effectives in other adverse conditions with impaired visibility, such as rainy weather or night condition.

The analysis of driver characteristics suggests that gender should be considered as an important factor for predicting the grade-crossing-crash risk. Overall, male drivers showed better performance than female drivers, but the gender difference was reduced by using PSM and IVAW. The system seems to be more effective for professional drivers, whereas nonprofessional drivers who made a go decision showed more hesitation and increased the likelihood of vehicle-train crash.

In summary, the study explored how foggy condition, gender, vocation, and FLTT affected drivers' performance at flashing-light-controlled grade crossings. The results prove the effectiveness of traffic signs design and IVAW, and suggest the combination use of countermeasures to maximize the safety benefits. The FLR warning system designed in the study was effective in enhancing drivers' performances and assisting drivers to safely pass through the grade crossings. It implies that the two-stage IVAW matched with PSM not only provides real-time and higher security, but also enhances the reliability of the system by PSM. Moreover, the system was capable to mitigate the negative effects of foggy weather and reduce drivers' individual difference during the crossing process, which indicates that the system has good applicability and adaptability. Findings of the study provide important guidance for the traffic control, infrastructure design, and driver assistance system development regarding grade crossings in China.

7. Limitations and Future Research

The study provided a pioneer research toward the understanding of grade-crossing-approaching behaviors under different factors' effect. A main limitation of the current study is that the BRT and RCT are relative values, which cannot be directly used as a reference for engineering standards. The limitation could be compromised by using supplementary measures, e.g., eye movement to detect the time when drivers actually perceive the traffic signs and flashing lights. Although the IVAW provides a positive impact on driver behavior over conventional flashing lights, the detailed design features need further modification/establishment before more concrete conclusions can be drawn. Examples of design features include the choice of words and delivery time of audio warning messages. Additionally, we did not consider the effect of age on driving performance in the experiment design. Previous studies sufficiently proved that aging affects the injury severity rate and driving performance [46, 62, 63]. Thus, it is suggested to explore the effects of age on grade-crossing-approaching behaviors in future research.

Data Availability

The behavioral data used to support the findings of this study are restricted by the independent ethics committee (IRB) in order to protect the privacy of participants.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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