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Research Article

The Influence of Figures in Warning Signs at the Manual Toll Station on the Lane Change Timing of Drivers in the Context of Virtual Reality of High-Proportion ETC Vehicles

Su Zhi,[1] **Peng Qunjie**,[2] **Wang Chaolun**,[1] **Xiang Wang**,[1] **and Ling Chen**[3]

[1]*Changsha University of Science and Technology, Changsha 410076, China*
[2]*Shenzhen Transportation Design & Research Institute CO., LTD, Shenzhen 518003, China*
[3]*College of Engineering and Design, Hunan Normal University, Changsha 410081, China*

Correspondence should be addressed to Ling Chen; chenling81@hunnu.edu.cn

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The increase of ETC (electronic toll collection system) vehicles on expressways has changed the proportion of ETC/MTC (manual toll collection system) lanes at toll stations. Based on a driving simulator, three toll gate lane warning sign schemes (scheme for present situation, MTC guidance scheme, and arrow + MTC guidance scheme) were proposed in this study. Driving simulation experiments were conducted to study the influence of figures in warning signs at the manual toll station on the lane change timing of drivers. It was found that the addition of arrows to the warning signs can significantly shorten the response time and guide the driver to make lane change decisions earlier to reduce the congestion between MTC vehicles and the mainline ETC vehicles at the toll plaza, thereby improving the traffic capacity and safety.

1. Introduction

In recent years, under the promotion of the Ministry of Transport, China, the proportion of ETC (electronic toll collection system) vehicles on expressways has gradually increased, thus adjusting the proportion of ETC/MTC (manual toll collection system) lanes at toll stations, which has correspondingly changed the behaviors and preferences of drivers. Therefore, with the rapid increase in the proportion of ETC vehicles, the targeted design of warning signs is particularly important.

The design of toll station signs involves many disciplines, among which human factors engineering (HFE) takes an essential part that investigates the optimization of man-machine-environment systems from psychology and physiology to improve system efficiency and ensure human safety, health, and comfort [1]. When designing warning signs, information-rich ones are more in line with the ideas of cognitive ergonomics [2, 3]. Studies have optimized the design or evaluation of warning signs from the perspective of drivers according to the HFE, such as age, emotion, and preference, so as to reduce the traffic accidents caused by the misinterpretation to warning signs [4, 5] (He W [6–8]). In addition, studies have also found that gender, education level, monthly income, and nationality of drivers are related to the understanding of road signs, and male drivers have a better understanding than female ones (Hashim et al., 2002 [9, 10]). Some studies have analyzed the design of warning signs from the aspect of driving state, such as driver distraction (David, 2015 [8]). Furthermore, studies have explored the recognition, understanding, and response of drivers to warning signs in different contexts [11, 12] and investigated among dyslexia, understanding of sign, and situational awareness [10, 13].

Research on the design of warnings signs at toll stations has been helping the drivers to find the correct toll lane at the toll station by optimizing figures and text in the signs. By summarizing the results of previous field and laboratory experiments, Ullman et al. [14] found that graphic signage is easier to interpret for drivers who have difficulty

Table 1: Other information of the participants.

Information	Category	N	Proportion (%)
Average number of toll booths passing per year	0	10	23.26
	1~5	11	25.58
	6~12	8	18.6
	≥13	14	32.56
Average annual driving mileage (k km)*	<5	9	20.93
	5~10	9	20.93
	11~30	15	34.88
	≥31	10	23.26

understanding words. Zwahlen et al. (2000) analyzed the eye movement data and lane change behavior data and found that the graphic signs on the highway ground can guide the driver to change lanes earlier. Skowronek [15] improved the graphic signs on the Houston expressway overpass and found that graphic signs can improve drivers' understanding of signs and reduce the cost of sign production. Wang et al. [16] assessed the effects of adding graphics to changeable message signs and found most people responded to graphics significantly faster than text messages, particularly for elderly drivers. Huang and Bai [17] found the addition of graphic-assisted portable changeable message signs can reduce the speed of vehicles in front of the work zone through driving simulator experiments. The purpose of the traditional warning signs is to remind ETC vehicles to turn left in advance to enter the ETC lane on the left side of the toll station. However, under the background of a high proportion of ETC vehicles, ETC vehicles can enter ETC lanes without changing lanes. Therefore, in order to avoid congestion and collisions in the toll gate plaza, the signs to ETC vehicles should be replaced with those to MTC vehicles that should turn right and change lanes in advance. In order to simplify the sign content and enhance the guidance, the semiotic theory was introduced in this study [18, 19]. The arrow is the most directional graphic symbol in the traffic guidance design [20, 21]. Meng [22] pointed out that arrows have high functionality and good visual recognition capabilities, which makes people receive clear traffic guidance information at a certain distance in a short period of time. Zhang et al. [23] compared the fixation count (FC) and found that the triangular design of the arrow was the most attractive figure for the driver. The larger the FC in the observation area, the more important and prominent the area for the observer. Due to access issues and security concerns with field testing, virtual reality (VR) has become an important means of testing the efficacy of warning signs, which allows for effective verification of sign content and location settings. Previous studies have shown that virtual reality (VR) simulations can be used as an effective tool for studying driving behavior, such as driver visual demand [24], testing proposed positioning of road signs, and testing traffic-control devices [25, 26]. And, in a study, sponsored by the Federal Highway Administration, the American Association of State Highway and Transport Officials, and the National Cooperative Highway Research Program [27], the usefulness of virtual reality (VR) simulation in the road design process was also verified and the use of driving simulators was recommended to be promoted in the road design community.

2. Experimental Design

2.1. Experimental Participants. A total of 45 participants were recruited for this experiment, and finally, 43 participants completed the experiment for all scenarios, including 33 males and 10 females, aged 18–53 years (AV = 33.7, SD = 8.7), with 1–17 years of driving experience (AV = 4.3, SD = 3.5). Other information of the participants is shown in Table 1 below.

2.2. Experimental Equipment. The driving simulators from Changsha University of Science and Technology was adopted to experimentally study the effect of combined warning signs on driving behavior at mainline toll stations. The CSUST simulator is a high-performance, high-fidelity driving simulator with a linear motion base capable of operating with 3 degrees of freedom. It is composed of a full-size vehicle cabin (Ford Focus), environmental noise and shaking simulation system, digital video replay system, and vehicle dynamic simulation system. as shown in Figure 1.

2.3. Experimental Scenario Design. The toll station facilities and the exit warning signs were redesigned in this study. Nine ETC toll lanes and four MTC toll lanes were set at the toll station. Luo [28] points out that when the ETC utilization rate is greater than 90%, the capacity of the mixed toll station will increase with the number of ETC lanes and then smoothly, while when the ETC utilization rate is less than 90%, the capacity of the mixed toll station will decrease with the increase of the number of ETC lanes. Therefore, to make the capacity of the mixed toll station optimal, this paper chooses the background in which the proportion of ETC vehicles is above 90% for the study. According to the national standard (GB5768.2–2009), 2 km, 1 km, and 500m exit warning signs and exit warning (action point) signs should be set considering the actual design of the Yuehlin Expressway. Huang et al. [29] pointed out that, within 500m before the exit was an important location for vehicle lane change behavior, so the design of the exit warning signs mainly focused on the content of 500 m and the 1 km, 300 m, and 0 m signs. The content design of the signs should follow the principles of simplicity, guidance, and advance. In this test, a total of three combative mainline toll station warning

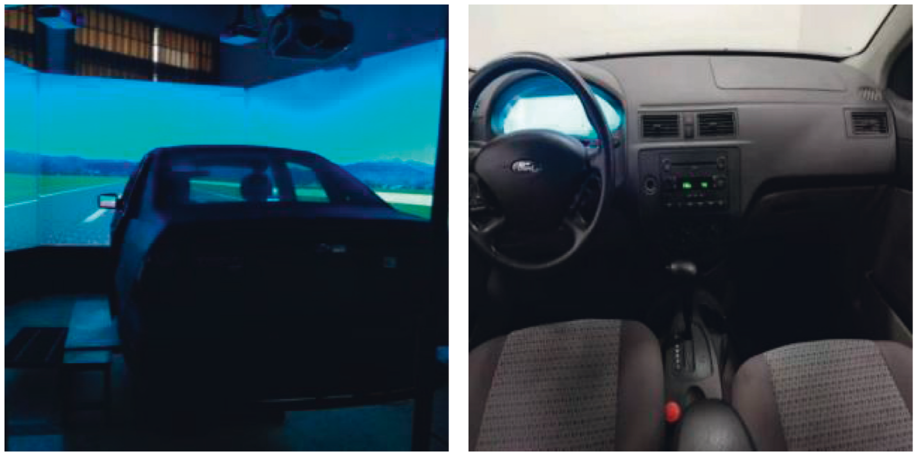

Figure 1: Driving simulator.

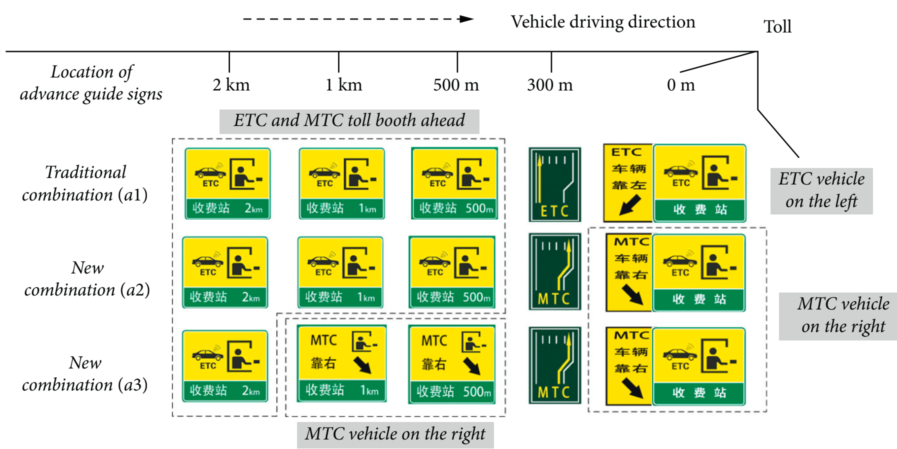

Figure 2: The three sign design schemes.

signs schemes were designed with the control variate method.

A status quo group (a1) was set up to study whether the existing scheme can still meet the traffic demand of a high proportion of ETC vehicles, which is the combination of the traditional signs. Experimental group 2 (a2), based on the status group, replaced the 300 m and 0 m signage ETC guidelines with MTC guidelines and replaced the arrow symbols inside the signage in order to have a better visual recognition function based on semiotic theory. Experimental group 3 (a3), based on experimental group 2 (a2), replaced the ETC guidance in the advance signage at 1 km and 500 m with MTC to the right and added corresponding text guidance, while guiding the text content of MTC to the right through the arrow to the right to enhance the readability of the message in accordance with the principle that arrows are the strongest image symbols in traffic guidance design in semiotic theory. The three sign design schemes are shown in Figure 2.

In this study, the experiment simulated a highway scenario in daytime with sufficient light, and to reduce the influence of extraneous environmental factors on driving behavior, the vehicle was an enclosed space and the interior temperature was 19~24°C, which is the appropriate temperature for humans. Given that there are two types of vehicle users in reality, each driver should complete the experiment as an ETC user and MTC user, respectively. Three experimental scenarios (a1–a3) and six experimental numbers (s1–s6) were set up in this experiment, as shown in Table 2.

2.4. Experimental Procedure

(1) Pre-experimental phase: participants adjusted their own seats to a suitable position and familiarized themselves with the simulated vehicle's throttle, brake, and steering, drove the simulated scenario, and checked whether they had any physical discomfort.

(2) Experiment preparation stage: the staff explained the precautions of the experiment for the participants and calibrated the driving simulators

(3) Formal experiment phase: one participant operated the driving simulation software. The whole experiment has three scenarios, the driver took part in the experiment with a different designated identity (ETC

Table 2: Experimental design grouping.

Experiment no.	Experimental identity	Experimental scheme	Warning sign combination
s5	ETC	a1	2 km, 1 km, 500 m, 300 m (ETC), 0 m
s1	MTC	a1	2 km, 1 km, 500 m, 300 m (ETC), 0 m
s6	ETC	a2	2 km, 1 km, 500 m, 300 m (MTC), 0 m (new)
s2	MTC	a2	2 km, 1 km, 500 m, 300 m (MTC), 0 m (new)
s4	ETC	a3	2 km, 1 km (new), 500 m (new), 300m (MTC), 0m (new)
s3	MTC	a3	2 km, 1 km (new), 500 m (new), 300 m (MTC), 0 m (new)

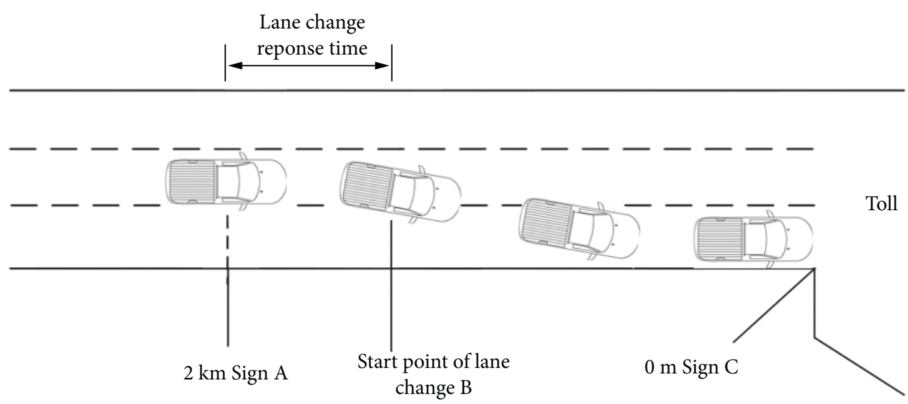

Figure 3: Lane change diagram.

Table 3: Results of descriptive statistical analysis of response time and analysis of variance test.

Driver	Category	N	Response time	
			Mean (s)	F value (P value)
Age	18~25	26	45.51	0.545 (0.653)
	26~35	35	49.31	
	36~50	25	40.37	
	≥51	10	46.15	
Gender	Male	72	44.32	0.698 (0.406)
	Female	24	49.55	
Driving age	1~3	18	43.56	0.066 (0.936)
	4~10	58	46.13	
	≥11	20	46.02	
Average number of toll booths passing per year	0	19	47.32	0.440 (0.725)
	1~5	25	49.84	
	6~12	21	41.43	
	≥13	31	44.03	
*Average annual driving mileage (k*km)*	<5	17	51.33	0.897 (0.446)
	5~10	19	51.41	
	11~30	35	42.28	
	≥31	25	42.04	
Combination of warning signs	1	19	43.16	5.620 (0.005)
	2	38	55.95	
	3	39	36.77	

user or MTC user), with a 20-minute break after each experiment.

(4) At the end of the experiment, the participants filled in the evaluation questionnaire of the effectiveness of the combination of warning signs and the subjective evaluation form of the realism of the driving simulator according to their subjective feelings.

2.5. Data Collation. The amount of raw data generated by the driving simulator was very large and contained a large number of nonclosely related variables, so it cannot directly reflect the experimental results, and key variables were extracted from the original simulator data for the analyses. During the driving process from 2500m to 0m from the toll booth, the driver would notice five warning signs, which would lead to different driving behaviors due to decision-

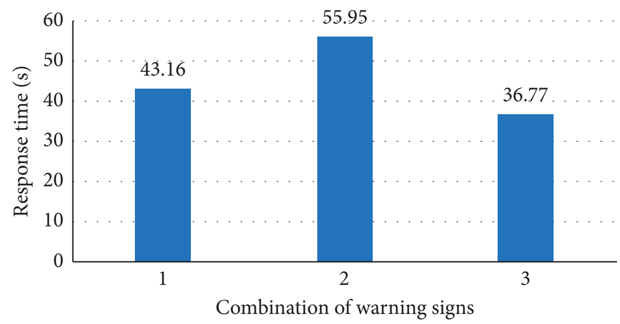

Figure 4: Mean value chart of time-based indicators.

Table 4: Results of descriptive statistical analysis of start position of lane change and analysis of variance test.

Driver	Category	N	Start position of lane change	
			Mean (m)	F value (P value
Age	18~25	26	818.71	1.452 (0.233)
	26~35	35	675.18	
	36~50	25	708.93	
	≥51	10	442.87	
Gender	Male	72	712.19	0.214 (0.644)
	Female	24	658.00	
Driving age	1~3	18	895.19	1.811 (0.169)
	4~10	58	661.60	
	≥11	20	629.17	
Average number of toll booths passing per year	0	19	780.11	1.540 (0.210)
	1~5	25	549.18	
	6~12	21	620.42	
	≥13	31	794.21	
*Average annual driving mileage (k*km)*	<5	17	749.81	1.104 (0.352)
	5~10	19	521.28	
	11~30	35	713.26	
	≥31	25	778.20	
Combination of warning signs	1	19	691.33	13.142 (0.000)
	2	38	439.19	
	3	39	955.01	

making. Humans do not respond to external stimuli directly, with delay and uncertainty. Therefore, participants' motivation to change lanes is a cumulative stimulus response to the warning signs. The differences in driver motivation to change lanes are related to individual differences and scenario factors.

The driver's motivational behavior for lane change was analyzed in the simulation experiments, so the parameters measured included response time, lane change start position, and speed.

The response time refers to the time from the 2 km warning sign to the start point of the lane change, denoted as AB, as shown in Figure 3. The start position of the lane change is the distance from the 0 m sign at the moment the driver starts the lane change, and the speed at the start of the lane change is the instantaneous speed at the start of the lane change.

To analyze whether different levels of a single independent variable (combination of warning signs and driver characteristics) have an effect on the dependent variable (motivation to change lane), the dependent variables were analyzed using one-way ANOVA. The hypothesis testing in the following analyses was based on a significance level of 0.05.

3. Result

The experiment recorded 129 complete participants of 43 participants experiencing three combination of warning signs. The vast majority of ETC users would choose to maintain their lanes because there was no lane change motivation, so this study only investigated the driving behavior of lane change participants. For the MTC participants, 96 times of advanced lane change were observed; therefore, the total sample (N) is 96.

3.1. Response Time. As shown in Table 3, the response time of lane change was only significantly related to the different combinations of signs (F $(2.93) = 5.620$, $P = 0.005$). After LSD postinspection, there was a significant difference between scheme 3 and scheme 1 ($P = 0.001$), as shown in

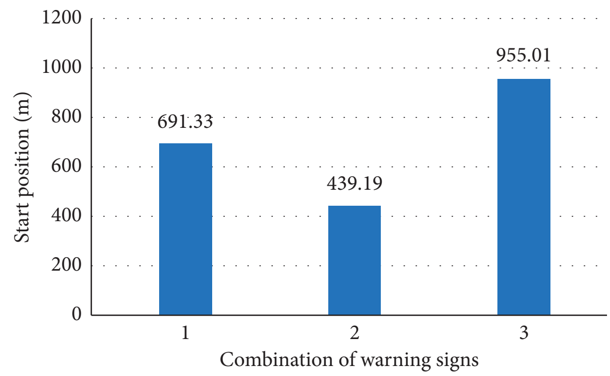

Figure 5: Mean value of start position under different combinations of sign schemes.

Table 5: Results of descriptive statistical analysis of speed at the start of a lane change and analysis of variance test.

Driver	Category	N	Speed at the start of a lane change	
			Mean (km/h)	F value (P value)
Age	18~25	26	92.68	1.361 (0.260)
	26~35	35	78.84	
	36~50	25	102.68	
	≥51	10	85.99	
Gender	Male	72	89.18	0.017 (0.896)
	Female	24	90.62	
Driving age	1~3	18	101.07	0.317 (0.813)
	4~10	58	82.81	
	≥11	20	98.68	
Average number of toll booths passing per year	0	19	91.03	1.540 (0.210)
	1~5	25	84.77	
	6~12	21	85.16	
	≥13	31	95.45	
Average annual driving mileage (k^*km)	<5	17	96.31	0.518 (0.671)
	5~10	19	88.62	
	11~30	35	93.32	
	≥31	25	80.36	
Combination of warning signs	1	19	81.52	0.677 (0.511)
	2	38	87.18	
	3	39	95.76	

Figure 4, and the response time of lane change in scheme 3 (36.77s) was significantly shorter than that of scheme 1 (43.16 s). This indicated that guiding the MTC vehicles can shorten the response time of MTC vehicles.

3.2. Start Position of Lane Change. As shown in Table 4, the initial position of the lane change was only significantly related to the different combination of sign schemes (F (2.93) = 13.142, $P < 0.001$), and after LSD postinspection, there was a significant difference between scheme 3 and scheme 1 ($P = 0.035$) and scheme 2 ($P < 0.001$), as shown in Figure 5. The initial lane change in scheme 3 (995.01 m) position was significantly longer than the initial position in scheme 1 (691.33 m) and scheme 2 (439.19 m), indicating that the guidance to MTC vehicles could make vehicles make lane changes earlier.

3.3. Speed at the Start of a Lane Change. As shown in Table 5, there was no significant relationship between the speed at the start of the lane change and either driver characteristics or different combination of sign schemes.

4. Discussion

Under the background that the proportion of ETC vehicles exceeds 90%, the existing notice signs in front of toll stations reduce the operational efficiency and safety of the toll lanes, cause traffic congestion, and pose a safety hazard.

In this paper, by replacing the warning sign with those for MTC vehicles to change lanes in advance and introducing semiotics theory, the content of the warning sign combination in front of the expressway toll station was redesigned. It can be seen from the experimental results that the combination of different warning signs has different effects on the response time and the starting position of the lane change.

The combination of different warning signs has different effects on the response time and the starting position of the lane change. Among the three schemes, the driver's response time under scheme 2 is the longest, 29.6% longer than the original scheme. This indicated that scheme 2 has a negative impact on the driver's content design. Comparing schemes 1 and 2, the relevance of signs within 1 km of scheme 2 is poor. There are not only MTC vehicle guidance but also ETC vehicle guidance. According to GB5768.2–2009, expressway road signs should follow the association principle. Because the poor content relevance between the various signs makes it hard for the driver to understand the content of the signs during driving, thereby increasing the response time. However, scheme 3, which satisfies the correlation and order between signs and adds arrow guidance, has the best driver response, 14.8% lower than the original scheme. This demonstrated that setting up reasonable and scientific warning signs can satisfy drivers' visual recognition needs for traffic information on expressways [30].

The combination of different warning signs has different effects on the response time and the starting position of the lane change. The lane change position of scheme 3 is the farthest from the toll plaza, followed by scheme 1. Scheme 2 is the worst. However, the response time of scheme 2 is prolonged, which leads to the driver's lane change starting position being closer to the toll station. When the lane change position is closer to the end of the lane, the driver may adopt more aggressive and dangerous forced lane changes [31, 32]. Compared with schemes 1 and 2, scheme 3 with arrow guidance allows the driver to start the lane change earlier due to the reduction in response time, thus making the initial position of the lane change earlier. This shows that the graphic sign with the arrow guidance can guide drivers to make lane-changing decisions earlier and reduce traffic accidents [14].

Regarding the speed at the beginning of the lane change, different schemes have no significant effect on this. The reason may be that the traffic flow in the experiment was free traffic, so the driver's perception of speed was not obvious. Therefore, there was no significant difference between the speed at the beginning of the lane change under different schemes.

Limitations of the study should be pointed out. Since this experiment was actually carried out under free traffic flow, the driver's perception of speed was not strong. It is recommended to further study the driver's motivation for lane changing under different traffic flows and vehicle types in future experiments, for example, under high, medium, volume traffic, to verify how the toll warning graphic affects the timing of driver lane changes.

5. Conclusion

The influence of figures in warning signs at the manual toll station on the lane change timing of drivers in the context of virtual reality of high-proportion ETC vehicles was investigated based on driving simulator. It was found that the addition of arrows to the warning signs can significantly shorten the response time and guide the driver to make lane change decisions earlier to reduce the congestion between MTC vehicles and the mainline ETC vehicles at the toll plaza, thereby improving the traffic capacity and safety.

Data Availability

All data are received based on driving simulation experiment and did not relate to publicly archived datasets.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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