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Research Article

Effects of Safety Facilities on Driver Distance Perception in Expressway Tunnels

Leyu Wei, Jinliang Xu, Xingli Jia, Xiaodong Zhang, and Haoru Li

School of Highway, Chang'an University, Middle Section of South 2 Ring Rd., Beilin District, Xi'an, Shaanxi 710064, China

Correspondence should be addressed to Jinliang Xu; xujinliang@chd.edu.cn

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We investigated the effects of four safety facilities in expressway tunnels—information boards, flashing lights, human-voice broadcasts, and siren broadcasts—on driver distance perception by questionnaire surveys and field experiments. Results from a survey questionnaire given to 436 drivers indicated that each of the facilities, except the human-voice broadcast, was perceived to increase the driving safety. Consistently, results from field experiments involving 150 participants in China's Xingshuliang Tunnel indicated that information boards, flashing lights, and siren broadcasts increased the distance perception accuracy of drivers, while human-voice broadcasts decreased this accuracy. The results of human-voice broadcasts may be due to the fact that drivers could not catch and understand the information they heard from human-voice broadcasts while driving in tunnels. This research can assist engineers in identifying the effective safety facilities in tunnels and provide a basis for prioritizing the implementation of these facilities, ultimately increasing driver distance perception accuracy and decreasing rear-end collisions.

1. Introduction

Expressway tunnels play an enormous role in transportation systems to make travelling convenient and fast; however, the constantly increasing tunnel accidents become a big problem for the safety of expressway operation. It is generally accepted that the frequency of rear-end collisions is the highest among the tunnel accidents that lead to large fatalities, casualties, and economic damage. In Norway's one-way, two-lane expressway tunnels, Amundsen and Ranes [1] found that approximately 62% of the traffic accidents involved rear-end collisions. Similarly, in China's expressway tunnels, Ma et al. [2] found that almost 57.5% of the 134 traffic accidents involved rear-end collisions. The Handbook of Tunnel Fire Safety [3] and Singapore accident statistics [4] also confirmed that rear-end collisions were the most commonly occurring accidents in expressway tunnels.

Several factors contribute to the occurrence of a rear-end collision in an expressway tunnel, and human perception is the key factor. Driving in a dark and enclosed tunnel can be monotonous and may lead to physical fatigue and cognitive distraction [5]. In addition, many drivers tend to travel more closely to the vehicle ahead of them, perceiving a longer distance between vehicles in tunnels [6]. When an emergency arises, those travelling too close to the lead vehicle may not have time to react appropriately, resulting in a rear-end collision. To effectively reduce rear-end collisions in expressway tunnels, it is important to learn more about the role of human perception and, in particular, driver distance perception.

Various facilities or devices including flashing lights, information boards, cable broadcasts, pavement markings, speed bumps, and delineators have been used to improve driver's perceive accuracy in tunnel environments [7]. In China, detailed specifications effectively guide engineers in the design of conventional expressway facilities and devices [8, 9]; however, such specifications are lacking for expressway tunnels. Instead, Chinese engineers must rely upon their prior project experience and published research when designing expressway tunnel facilities and devices. An enhanced understanding of driver distance perception and the associated effects of various safety facilities in tunnels would provide a basis for engineering design.

Previous studies investigating driver distance perception commonly use survey questionnaire or interview methods

to reflect a driver's subjective experience. Considering a driver's sensory, cognitive, physical, and functional affordance, Ronchi and Nilsson [10] surveyed 62 drivers regarding the design and function of information signs and flashing lights of tunnels and recommended that any sign text should be displayed in an amber color to better capture a driver's attention. They also assessed the effect of acoustic systems in road tunnels and suggested that human-voice broadcasts should be avoided because a driver may not hear or distinguish messages in a noisy tunnel environment. However, their study of acoustic systems was mainly based on theoretical analysis and lacked experiment evidence. Further surveys are needed to confirm the effects of human-voice broadcast and siren broadcasts. Dudek and Ullman [11] compared the effect of flashing messages, flashing lines, and alternating lines on a variable message sign based on the reading time, response time, and level of comprehension reported by 260 Texas drivers. They found that the average reading time was significantly higher for flashing messages. Other studies [12, 13] have reported that a driver's reading comprehension can be increased with clear semantic sign messages and proper training.

As an alternative to survey questionnaires or interviews, select studies have investigated the effects of safety facilities using field experiments conducted in real tunnels or driving simulators. During the experiments, specialized devices were used to measure dynamic driver data such as heart rate, eye movement, myoelectricity, skin temperature, and respiration depth. In addition, driving behaviors such as driving speed, acceleration, distance to the nearest wall, and overtaking rate can be measured [14]. For example, Manser and Hancock [15] used a driving simulator to determine that wall pattern design significantly affects a driver's speed control and perception.

Some debate exists regarding the ability of driving simulators to accurately replicate driving experience and associated driver behavior in real tunnels. Select studies found that driver performance was similar in virtual and real environments [16–18], while other studies reported a significant difference in driver behavior in these two environments [19, 20]. For example, driving speed was higher and vehicle distance to the nearest tunnel wall was much lower in simulated tunnels as compared with real tunnels. This phenomenon may be attributable to a driver's lower stress level in a driving simulator or their feelings of dizziness and nausea when using the virtual visual equipment [21]. This ongoing debate regarding the accuracy of driving simulators suggests that field experiments conducted in real tunnels are more robust.

Previous research has shown that safety facilities in tunnels significantly affect a driver's speed perception and concentration [22, 23], but few studies have considered the relationship between driver distance perception and these facilities. According to statistics, rear-end collision accidents in tunnels are mainly caused by passenger cars and trucks, accounting for 42.18% and 56.25% of tunnel accidents, respectively [24]. It is important for both truck drivers and passenger car drivers to estimate distance right and maintain a safety distance from vehicles in front of them. In addition, information boards, flashing lights, human-voice broadcasts, and siren broadcasts are the most common safety facilities in China's expressway tunnels. Information boards and flashing lights primarily affect a driver's visual perception, and cable broadcasts using a human voice or siren affect a driver's audio perception. The research on the effects of these four facilities is very important and necessary for road traffic safety. In this study, we investigated the effects of four types of safety facilities of expressway tunnels—information boards, flashing lights, human-voice broadcasts, and siren broadcasts—on distance perception of passenger car drivers and truck drivers. To support this study's objective, a survey questionnaire was administered to 436 drivers at two expressway service areas. Complementing this qualitative data, field experiments involving 150 participants were conducted in the Xingshuliang Tunnel along the Yanxi Expressway in the Shaanxi Province of China. The results of this study can assist engineers in identifying the most effective safety facilities in tunnels and provide a basis for prioritizing their implementation, ultimately increasing driver distance perception accuracy and decreasing rear-end collisions.

2. Experimental Method

2.1. Questionnaire Survey. A questionnaire survey was conducted in Yaozhou and Huangling service areas along the Yanxi Expressway. Vehicle drivers and occupants possessing a valid driver's license were asked to independently complete questionnaires. When completing the questionnaire, drivers were first asked to provide basic demographic information (e.g., gender and age) as well as driving experience. Next, drivers were asked to assess the effects of the four safety facilities on their driving behavior using three indicators (e.g., increasing their attention, decelerating, or maintaining space between vehicles). Using a five-point Likert scale, a rank of "1" indicated a very negative effect on driving behavior, while a rank of "5" indicated a very positive effect on driving behavior. Higher rankings suggest a more effective facility [21]. The original Chinese version of the questionnaire was published on the website https://www.wjx.cn/jq/26197255.aspx, and the translated English version of the questionnaire could be found on the website https://www.wjx.cn/jq/26193643.aspx.

The minimum sample size required in this study was determined as follows:

$$N \geq \left(\frac{SK}{E}\right)^2 \tag{1}$$

where N is the sample size; S is the sample standard deviation; K is the z-score for a specified probability; and E is the allowable error. Assuming that S=0.5, K=1.96 (for a 95% confidence level), and E=5%, a minimum of 384 questionnaires was required.

In 2017, the statistics by Chinese ministry of public security showed that female drivers account for only 25% of the car drivers. Besides, few of the truck drivers are females because trucking is an intensive work that most of the female drivers could not handle. Considering the small proportion of the female drivers in China, fewer female drivers were investigated in both questionnaire surveys and field experiments.

Table 1: Installation setups in 5 experimental conditions.

Condition	Information Board	Flashing Light	Human-voice Broadcast	Siren Broadcast
1	×	×	×	×
2	√	×	×	×
3	×	√	×	×
4	×	×	√	×
5	×	×	×	√

Note: "√" means "activated"; "×" means "deactivated".

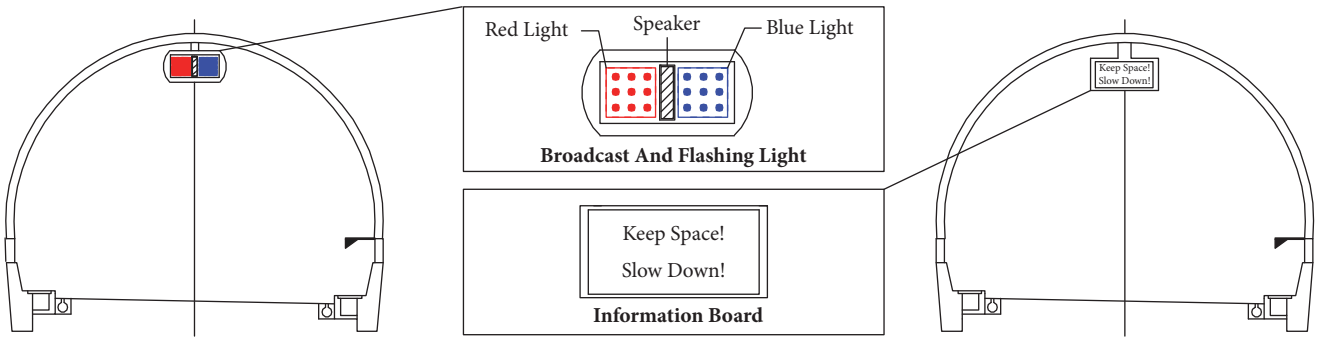

Figure 1: Safety facilities in the Xingshuliang Tunnel.

2.2. Field Experiment. To complement the qualitative survey questionnaire analysis, field experiments were conducted in the Xingshuliang Tunnel along the Yanxi Expressway in Shaanxi Province of China. The Xingshuliang Tunnel, which is located between the Yaozhou and Huangling service areas, is a one-tube three-lane tunnel that is 1100 m long. Owing to the low traffic volume of the experimental road section, the traffic flow during field experiments could be considered as the free flow.

Drivers stopping at either the Yaozhou or Huangling service areas were invited to participate in the field experiments. Car drivers and truck drivers were invited to participate. Prior to participating, drivers were informed that they may be asked several simple questions regarding expressway tunnel facilities, but the specific study purpose was not disclosed.

During the experiments, the Xingshuliang Tunnel Monitoring Center, under our guidance, applied five different experimental conditions in the tunnel. As shown in Table 1, no devices were activated in condition 1, and only one type of facility was activated in the other four conditions. A driver would only participate in one experiment of the 5 conditions at a time. To ensure that the type of safety facilities is the only variable in this experiment, it is necessary to keep the characteristics of participates in each group homogeneous. Therefore, participates were divided into different groups according to their gender and age in order to ensure the demographic composition of each group similar. All of the field experiments were conducted during low traffic time period at the low volume road section to minimize the influence of road traffic flows on participants in the real environment.

Figure 1 shows the safety facilities in the tunnel. The information boards were located every 1 km and displayed "Keep Space! Slow Down!" when activated. The flashing lights and cable broadcasts were jointly mounted every 300 m. The red/blue flashing lights had a flash frequency of 180 times/min when activated. The cable broadcast system of the tunnel offered a human-voice or siren model. When the human-voice model was activated, a female voice broadcasted "Please slow down! Please keep space!"

Figure 2 shows the experimental setup used to determine driver distance perception accuracy. Two sets of flags (one yellow and two blue) were positioned outside and inside the tunnel. The distance between the yellow and nearest blue flag was 100 m and that between the blue flags was 60 m, representing a safe distance between vehicles at 60 km/h. To reduce the confounding effects of speed on a driver's visual perception during the experiments, each driver was required to travel at 60 km/h [15, 22]. When approaching the yellow flag, drivers were asked to estimate the distance between the two blue flags.

3. Data Analysis Method

3.1. Questionnaire Survey. To determine whether drivers subjectively perceived a safety facility to have a positive or negative effect on driver distance perception, survey questionnaire responses were analyzed using a one-sample t-test and nonparametric Wilcoxon sign test, with the neutral rank of 3 as the baseline. The t-tests would be applied when normality assumptions were satisfied otherwise the Wilcoxon sign test would be used. Rejection of the null hypothesis confirmed that devices ranked <3 and >3 negatively and positively affected driver behavior, respectively.

To better understand the effects of demographics and driving experience on the subjective device rankings, a

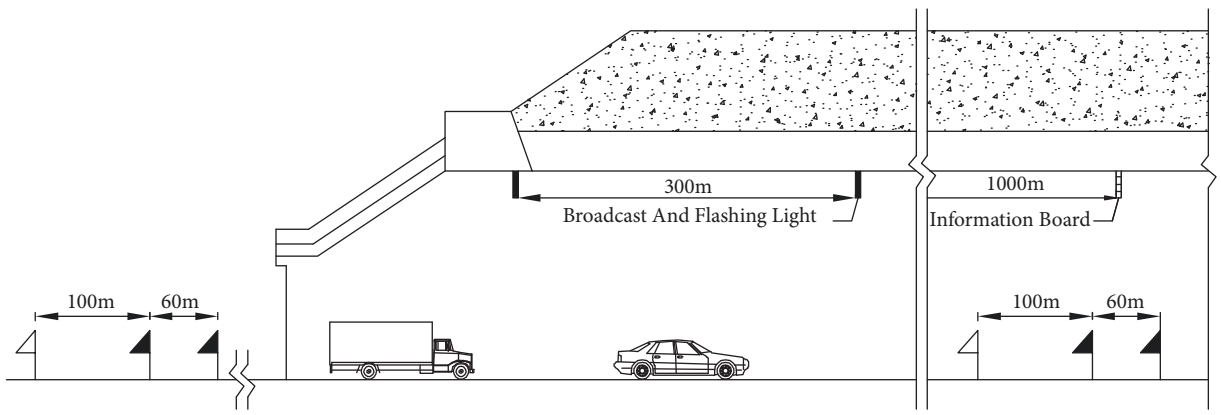

Figure 2: Driver distance perception measurement in the Xingshuliang Tunnel.

series of regressions were performed using an ordered logit regression model appropriate for the five-point Likert scale based data. For ordinal responses, ordered probit or logit models yield consistent and efficient estimates [25, 26]. In an ordered logit model, the probability of a response having a Likert rank j is determined as follows [27]:

$$\Pr\left(y_i > j\right) = \frac{\exp\left(X_i\beta' - \tau_i\right)}{1 + \exp\left(X_i\beta' - \tau_i\right)} \quad \mathrm{j} = 1, \ldots, 5 \tag{2}$$

where X_i is a (k×1) vector of observed nonrandom explanatory variables, β is a (k×1) vector of unknown parameters to be estimated, and τ_i is a (k×1) vector of unknown cut points to be estimated. The model parameters (β) and cut points (τi) are estimated using maximum likelihood methods [27]. When estimating an ordinal regression, a test of the parallel lines assumption was needed to verify that the slope coefficients did not vary over different alternatives [28]. If this assumption was violated, a generalized or partially constrained generalized ordered logit model would have been estimated instead [29, 30].

3.2. Field Experiment. In this study, the difference between the actual and estimated distance reflects a driver's distance perception accuracy. This error can be defined as follows:

$$e = \left|S_p - S_r\right|, \quad \left(S_p > 0,\ S_r > 0\right) \tag{3}$$

where S_p is the perceived distance (m) and S_r is the real distance (60 m).

Then, a driver's distance perception accuracy can be defined as follows:

$$\alpha = \frac{e}{S_r} = \frac{\left|S_p - S_r\right|}{S_r} = \left|\frac{S_p}{S_r} - 1\right|, \quad \left(S_p > 0,\ S_r > 0\right) \tag{4}$$

Driver distance perception accuracy is optimal when α=0. To introduce the effects of safety facilities on driver distance perception, individual accuracy values can be averaged for each set of drivers exposed to a particular safety device as follows:

$$\overline{\alpha} = \frac{1}{n}\sum_{i=1}^{n}\alpha\,(\mathrm{i}) \tag{5}$$

where i is the number of drivers exposed to one of the five experimental conditions.

To account for the differences in visibility and noise levels, we compared field measurements from outside and inside the tunnel and determined efficiency values for individual safety devices as follows:

$$\beta = \frac{1}{n}\sum_{i=1}^{n}\left(\frac{S_{P1}\,(i)}{S_{p2}\,(i)} \cdot \frac{S_{r1}\,(i)}{S_{r2}\,(i)}\right) \tag{6}$$

where S_{p1}(i) and S_{p2}(i) are the perceived distances for driver i and S_{r1}(i) and S_{r2}(i) are the real distances (60 m) for driver i inside and outside the tunnel, respectively. A higher β value suggests higher safety device performance.

4. Results and Discussion

4.1. Questionnaire Survey. In total, 461 drivers at the Yaozhou and Huangling service areas were recruited to fill the questionnaire. However, some respondents did not answer all questions on the paper, and these incomplete questionnaires were excluded from the final sample. Therefore, only a total of 436 valid responses were considered for the data analysis (> 384).

Of the 436 respondents, 83.03% were males and 16.97% were females. Most respondents were aged between 26 and 35 yr (35.09%) or 36 and 45 yr (30.27%). Respondents aged between 18 and 25, 46 and 55, and 56 and 65 yr accounted for 10.55%, 15.83%, and 8.26% of the sample, respectively. With respect to driving experience, most respondents reported driving for >6 yr (51.33%). Respondents who reported driving for <1, 1–3, and 4–6 yr accounted for 6.67%, 28%, and 14% of the sample, respectively.

Uniquely, cable broadcasts in tunnels are deactivated in most of the time and only activated for special situations or emergencies like severe weather events, traffic accidents, and

Table 2: Subjective effects of safety facilities on driver behavior.

Safety facility	Driver behavior	Very negative 1	Slightly negative 2	Neutral 3	Slightly positive 4	Very positive 5	Mean	Standard Deviation
Information boards	Increase attention	4.36	5.96	8.72	56.19	24.77	3.91	0.98
	Decelerate	4.13	8.49	9.63	24.54	53.21	4.14	1.15
	Keep space	10.32	7.11	11.47	44.04	27.06	3.70	1.23
Flashing lights	Increase attention	2.06	1.61	22.71	35.09	38.53	4.06	0.93
	Decelerate	2.98	4.13	18.81	37.39	36.70	4.01	0.99
	Keep space	6.42	13.07	25.00	22.48	33.03	3.63	1.24
Human-voice broadcasts*	Increase attention	0.00	7.57	5.28	46.33	40.83	4.20	0.85
	Decelerate	0.00	5.28	4.36	36.70	53.67	4.39	0.80
	Keep space	28.21	26.61	13.53	20.64	11.01	2.60	1.37
Siren broadcasts*	Increase attention	2.52	19.27	1.83	26.38	50.00	4.02	1.23
	Decelerate	3.67	3.21	10.32	34.86	47.94	4.20	1.00
	Keep space	15.60	22.71	11.01	34.17	16.51	3.13	1.35

∗Note: 42.2% of drivers had never heard cable broadcasts and based responses on expectation not experiences. Analyses excluding these 42.2% of participants showed a similar pattern to those reported in Table 2.

road maintenance. As such, 42.2% of those drivers had never heard cable broadcasts in tunnels and filled the questionnaire based on their expectation instead of experience. Statistics tests indicated that the results of respondents who have experienced the cable broadcasts were similar to that of all respondents.

Table 2 summarizes the subjective effects of the four safety facilities on driver behavior in tunnels based on the five-point Likert scale. It is shown that all of the questionnaire responses followed abnormal distribution, so the Wilcoxon sign tests were applied to all cases. All of the Wilcoxon sign tests rejected the null hypothesis that the mean ranks were equal to the neutral rank of 3 at the 99% confidence level.

According to the survey, drivers considered that all of the four facilities had a positive effect (>3) on their willingness to increase attention and decelerate their vehicle. It was also believed that each of the facilities was useful (>3) for drivers to maintain the distance, except the human-voice broadcasts (<3). Additional Kruskal-Wallis tests were applied to specifically compare the subjective perception of the safety facilities. The asymptotic significance of "increase attention" function, "decelerate" function, and "keep space" function were all 0 (<0.05). It can be inferred that people generally considered that the most helpful safety facility for increasing attention (4.20) and slowing down (4.39) was the human-voice broadcast, and the most effective safety facility for keeping a safety distance (4.14) between vehicles was the information board.

For information boards, the mean value of decelerating was the highest in all functions. Respondents reflected that the messages on the information boards could usually remind them of the speed limit and encourage them to apply their brakes to avoid a fine. Human-voice and siren broadcasts in tunnels were reportedly most effective for encouraging drivers to decelerate (4.39 and 4.20, respectively) and increase their attention (4.20 and 4.02, respectively). Most notably, human-voice broadcasts had a negative effect (<3) on encouraging drivers to maintain adequate spacing between vehicles. When cable broadcasts were activated, most drivers realized that a serious event has occurred, and they would slow down and increase their attention accordingly. At the same time, they were anxious to exit the tunnel and followed the lead vehicle more closely. Flashing lights, which create a strong visual stimulation for drivers in dark tunnels, were most effective for encouraging drivers to increase their attention (4.06) and decelerate (4.01). These findings suggest that flashing lights can effectively evoke immediate reactions that do not require complex thought (e.g., applying brakes or increasing attention) but are less effective for complex reactions such as estimating and responding to distance changes between vehicles.

Regarding any confounding effects on the subjective facility rankings, results of the ordered logit model indicated no age or driving experience effects for any of the reported driving behaviors. Gender, however, affected several of the reported driving behaviors. Table 3 summarizes these model results. Compared to female respondents, male respondents were more likely to increase attention but less likely to decelerate when exposed to information boards. Comparatively, female respondents were more likely to maintain adequate distance when exposed to flashing lights, while males were unaffected. Cable broadcasts had a positive and negative effect on distance maintenance for males and females, respectively. These collective results suggested that male respondents were more confident in their driving skills, more rational when facing complex situations, and less

Table 3: Ordered logit model results regarding gender effects on driver behavior.

Driver behavior	Information boards		Flashing lights		Human-voice broadcasts		Siren broadcasts	
	Coefficient	p	Coefficient	p	Coefficient	p	Coefficient	p
Increase attention	-0.275	0.009	-0.413	<0.001	-0.403	<0.001	-0.423	<0.001
Decelerate	-0.297	0.005	0.228	0.040	-0.421	<0.001	-0.452	<0.001
Keep space	-0.427	<0.001	0.236	0.032	0.317	0.005	-0.210	0.047

Table 4: Distance perception accuracy (α) and device efficiency (β) statistics.

Driver group	N	α		β	
		Mean	Standard deviation	Mean	Standard deviation
1 Control Group	30	0.16	0.0903	0.63	0.1322
2 Information Board Group	30	0.09	0.0775	0.78	0.1911
3 Flashing Light Group	30	0.12	0.0955	0.76	0.1710
4 Human-voice Broadcast Group	30	0.25	0.1025	0.52	0.1640
5 Siren Broadcast Group	30	0.13	0.0947	0.73	0.1516

Table 5: ANOVA of distance perception accuracy among driver groups.

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	.478	4	.120	13.983	.000
Within Groups	1.240	145	.009	—	—
Total	1.718	149	—	—	—

affected by safety facilities. Female drivers were more cautious and less confident in their driving skills, less calm under pressure, and more affected by safety facilities.

4.2. Field Experiment. Results of the field experiments were based on the behaviors of 150 drivers (90 car and 60 truck drivers). Thirty drivers (18 car and 12 truck drivers) were exposed to one of the five experimental conditions. The sample was predominantly male, comprising only 16 female passenger cars (17.7%) and no female truck drivers. As mentioned before, the number of female drivers is much less than male drivers in China. In addition, only few of the females work for truck transportation since truck driving is a labor-intensive work for them. The few female drivers we encountered at the expressway service areas often rejected the request to participate in experiments owing to their security concerns. The age of participants ranged from 18 to 59 yr (36.64±12.78 yr), and the average driving experience was 7.38±3.81 yr.

Table 4 summarizes the mean and standard deviation values for a driver's distance perception accuracy (α) and for an individual safety facility's efficiency (β) when exposed to individual safety facilities. The mean accuracies for drivers exposed to information boards, flashing lights, and siren broadcasts (groups 2, 3, and 5, respectively) were lower (α=0 is optimal) than the mean accuracy for drivers exposed to no devices (group 1). It can assume that information boards, flashing lights, and siren broadcasts were effective for improving driver distance perception in tunnels. To verify this assumption, further comparisons of distance perception accuracy between groups were needed. Besides, human-voice broadcasts decreased distance perception accuracy by almost 56.25%. During the field experiments, several drivers complained that they could not hear the message of human-voice broadcast clearly, and a few drivers even opened car windows to hear it.

To further confirm the effects of safety facilities on driver distance perception, ANOVA (the Analysis of Variance) was used to compare driver groups 1–5. The homogeneity test of variances proved that ANOVA was appropriate and effective ($p=0.52>0.05$). The results of ANOVA are summarized in Table 5. There existed significant difference of distance perception accuracy between these groups ($p<0.05$). To further study the significant level of safety facilities, LSD (least-significant difference) were made to calculate multiple comparisons and the results are shown in Table 6.

By comparison between group 1 and groups 2-5, a driver's distance perception accuracy was significantly different when exposed to information boards and human-voice broadcasts. According to the Letter Marking Method, the distance perception accuracy of information boards, flashing lights, and siren broadcasts wasclassified as the first level, the distance perception accuracy without devices was classified as the second level, and the distance perception accuracy of human-voice broadcast was classified as the third level. The order of effectiveness of tunnel safety facilities was consistent with results in Table 4.

Generally, information boards provide clear and simple message to guide drivers, and they do not create tense atmosphere as broadcasts do. Compared with information boards, siren broadcast is usually loud and harsh to catch people's

Table 6: Multiple comparisons of distance perception accuracy among driver groups.

Group I	Group J	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
1*	2	.069444445	.023877258	.004	.02225201	.11663688
	3	.040555556	.023877258	.092	-.00663688	.08774799
	4	-.094444444	.023877258	.000	-.14163688	-.04725201
	5	.031666667	.023877258	.187	-.01552577	.07885910
2*	1	-.069444445	.023877258	.004	-.11663688	-.02225201
	3	-.028888889	.023877258	.228	-.07608132	.01830355
	4	-.163888889	.023877258	.000	-.21108132	-.11669645
	5	-.037777778	.023877258	.116	-.08497021	.00941466
3*	1	-.040555556	.023877258	.092	-.08774799	.00663688
	2	.028888889	.023877258	.228	-.01830355	.07608132
	4	-.135000000	.023877258	.000	-.18219244	-.08780756
	5	-.008888889	.023877258	.710	-.05608132	.03830355
4*	1	.094444444	.023877258	.000	.04725201	.14163688
	2	.163888889	.023877258	.000	.11669645	.21108132
	3	.135000000	.023877258	.000	.08780756	.18219244
	5	.126111111	.023877258	.000	.07891868	.17330355
5*	1	-.031666667	.023877258	.187	-.07885910	.01552577
	2	.037777778	.023877258	.116	-.00941466	.08497021
	3	.008888889	.023877258	.710	-.03830355	.05608132
	4	-.126111111	.023877258	.000	-.17330355	-.07891868

*Note: 1: control group, 2: information board group, 3: flashing light group, 4: human-voice broadcast group, and 5: siren broadcast group.

attention, but it does not transmit explicit instructions for drivers. Human-voice broadcasts contain specific directions; however, it is hard to clearly catch the words and follow them. Therefore, the information board performs better in improving distance perception ability, and cable broadcast in tunnels is not always helpful for drivers to drive safely.

The noise inside tunnels is normally 10~20 dB larger than outside tunnels, and the reverberation time is probably 5~10 s [31]. For long tunnels, when play cable broadcast, tunnel walls will strengthen the noise level and reverb effects more than usual [32]. To solve this problem, the decibel level and arrangement distance of broadcast should be further studied to decrease echo and reverberation effect in tunnels. Recently, advanced technology of wireless broadcast applying in expressway tunnels has been developed to achieve the goal that people could listen to specific radio in vehicles [33, 34]. It seems that wireless tunnel radio in vehicles would totally solve the problem of echo and reverberation and make it possible to transit more information without clear sound concern. Some other problems will appear, such as that drivers can only hear wireless broadcast instructions only if their car radios are turned on.

An individual safety device's efficiency (β), which accounted for differences in visibility and noise levels outside and inside the tunnel, varied based on the driver. Figure 3 shows the distribution of β values across the sample. For drivers exposed to information boards, flashing lights, siren broadcasts, no facilities, and human-voice broadcasts, the range of β values was 0.450–1.256, 0.356–1.167, 0.356–1.000, 0.381–0.857, and 0.296–0.857, respectively. Compared with outside the tunnel, driver distance perception inside the tunnel improved when exposed to information boards, flashing lights, and siren broadcasts. Conversely, driver distance perception declined when exposed to human-voice broadcasts inside the tunnel as compared with outside the tunnel. Nearly 13% of the β values for information boards and flashing lights were larger than 1, indicating that driver distance perception was better inside rather than outside the tunnel.

The results of field experiments indicated that the human-voice broadcast did little contribution on distance perception, and the results of questionnaire survey also showed that people generally believed that the human-voice broadcast against them to keep space from vehicles ahead.

One limitation should be noted regarding this study's findings. Driving speed has been shown to significantly affect a driver's perceived distance; higher vehicle speeds result in lower perceived distances [17, 23, 24]. As such, drivers participating in this study's field experiments were required to drive at a speed of 60 km/h. Because it was difficult for drivers to maintain a constant speed of 60 km/h, the perceived distances obtained in this study may include small errors.

5. Conclusion

Information boards, flashing lights, and cable broadcasts are the most common safety facilities used in expressway tunnels. Despite their prevalence, few studies have confirmed the effects of these facilities on driver distance perception and associated rear-end collision rates in tunnels. In this study, we investigated the effects of four safety facilities—information

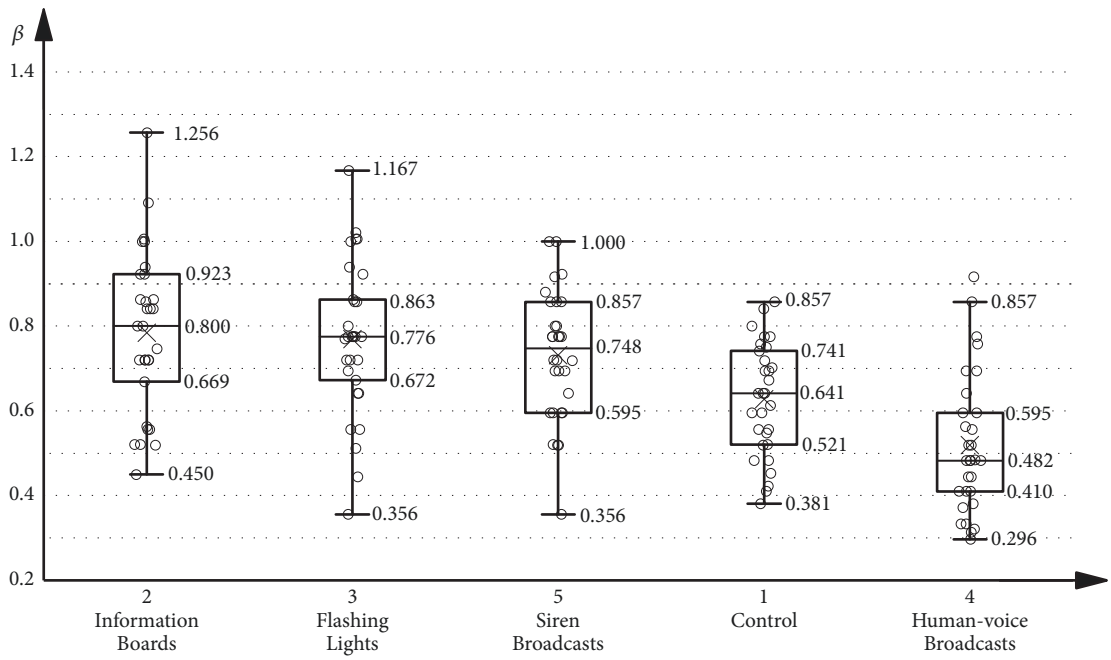

Figure 3: Sample distribution of facility efficiency (β).

boards, flashing lights, human-voice broadcasts, and siren broadcasts—on driver distance perception in expressway tunnels. A survey questionnaire was given to 436 drivers at two service areas along the Yanxi Expressway in Shaanxi Province of China. In addition, field experiments involving 150 participants were conducted in the Xingshuliang Tunnel along the Yanxi Expressway.

Results from the questionnaire survey indicated that drivers believed that information boards, flashing lights, and siren broadcasts were most effective (in descending order) in encouraging drivers to increase attention, decelerate, and maintain safe distance between vehicles. Human-voice broadcasts were positive in encouraging drivers to increase attention and decelerate but had a negative effect on distance maintenance of drivers. It could be explained that the information of human-voice broadcast in expressway tunnels was difficult for drivers to catch and understand. In this study, the questionnaire survey was mainly focused on the perceived effects of four safety facilities; however, how much better or worse with each safety facility to reduce crashes needs further study.

Based on the statistical analysis of the distance perception accuracy (α), the study of field experiments came to a conclusion that information boards, flashing lights, and siren broadcasts increased the distance perception accuracy of drivers, while human-voice broadcasts decreased this accuracy. There was no significant difference of distance perception accuracy between information boards, flashing lights, and siren broadcasts, and the distance perception accuracy of these three facilities was significant higher than without facilities. According to the calculation of individual safety device efficiency (β), for each safety facility in tunnels, the distance perception of information boards, flashing lights, and siren broadcasts performed better inside tunnels than outside tunnels.

The results of this study substantially contribute to the state of knowledge regarding the effects of safety facilities on driver distance perception. These findings can assist engineers in identifying the most effective safety facilities in tunnels and provide a basis for prioritizing their implementation, ultimately increasing driver distance perception accuracy and decreasing rear-end collisions.

Some of the differences of the results obtained from the questionnaire surveys and the field experiments may be contributed to the difference between the subjective judgement and objective behaviors. Some of the small differences of the results related to the cable broadcasts obtained in this study and other research may also be due to the 42.2% of responders who had never experienced cable broadcast in expressway tunnels. Also, the sample size of drivers, especially female drivers, was not large enough to represent the reactions of drivers in China; the real effects of each safety facility may be better or worse than the results in this research.

Despite these contributions, additional research is required in a number of areas. Future research focused on driver distance perception in tunnel facilities should consider the effects of alternative technologies (e.g., wireless broadcast systems) to improve human-voice broadcasts, the combined use of various safety devices (in this study, we considered each facility singularly), and alternate messaging and installation arrangements. A related study considering driver speed perception in tunnels could be combined with this study's findings to ultimately improve road safety. Besides, the effects of safety facilities of tunnels under special situations or emergencies should be further studied.

Conflicts of Interest

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

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References

[1] F. H. Amundsen and G. Ranes, "Studies on traffic accidents in Norwegian road tunnels," *Tunnelling and Underground Space Technology*, vol. 15, no. 1, pp. 3–11, 2000.

[2] Z. Ma, C. Shao, and S. Zhang, "Characteristics of traffic accidents in Chinese freeway tunnels," *Tunneling Underground Space Technology Incorporating Trenchless Technology Research*, vol. 24, no. 3, pp. 350–355, 2009.

[3] A. Beard and R. Carvel, *The Handbook of Tunnel Fire Safety*, Thomas Telford Publishing, 2005.

[4] Q. Meng and X. Qu, "Estimation of rear-end vehicle crash frequencies in urban road tunnels," *Accident; Analysis And Prevention*, vol. 48, no. 5, pp. 254–263, 2012.

[5] F. H. Amundsen, "Studies of driver behaviour in Norwegian road tunnels," *Tunnelling and Underground Space Technology*, vol. 9, no. 1, pp. 9–15, 1994.

[6] S. Bassan, "Overview of traffic safety aspects and design in road tunnels," *Iatss Research*, vol. 40, no. 1, pp. 35–46, 2016.

[7] Federal Highway Administration, "Manual on Uniform Traffic Control Devices for Streets and Highways," 2009.

[8] Ministry of Communications of PRC, *Guidelines for Design of Highway Safety Facilities: JTG D81-2006*, China Communications Press, 2006.

[9] Ministry of Communications of PRC, *Specification for Layout of Highway Traffic Signs and Markings: JTG D82-2009*, China Communications Press, 2009.

[10] E. Ronchi and D. Nilsson, *Traffic Information Signs, Color Scheme of Emergency Exit Portals and Acoustic Systems for Road Tunnel Emergency Evacuations*, Department of Fire Safety Engineering Lund University Sweden, 2013.

[11] C. Dudek and G. Ullman, "Flashing Messages, Flashing Lines, and Alternating One Line on Changeable Message Signs," *Transportation Research Record Journal of the Transportation Research Board*, vol. 1803, no. 1, pp. 94–101, 2002.

[12] Y.-K. Ou and Y.-C. Liu, "Effects of sign design features and training on comprehension of traffic signs in Taiwanese and Vietnamese user groups," *International Journal of Industrial Ergonomics*, vol. 42, no. 1, pp. 1–7, 2012.

[13] D. Shinar and M. Vogelzang, "Comprehension of traffic signs with symbolic versus text displays," *Transportation Research Part F Traffic Psychology and Behaviour*, vol. 18, no. 4, pp. 72–82, 2013.

[14] World Road Association, *Human Factors and Road Tunnel Safety regarding Users*, 2008.

[15] M. P. Manser and P. A. Hancock, "The influence of perceptual speed regulation on speed perception, choice, and control: Tunnel wall characteristics and influences," *Accident Analysis & Prevention*, vol. 39, no. 1, pp. 69–78, 2007.

[16] M. Lidström, "Using advanced driving simulator as design tool in road tunnel design," *Transportation Research Record Journal of the Transportation Research Board*, vol. 1615, no. 1, pp. 51–55, 1998.

[17] L. Domenichini, F. La Torre, D. Vangi, A. Virga, and V. Branzi, "Influence of the lighting system on the driver's behavior in road tunnels: A driving simulator study," *Journal of Transportation Safety & Security*, vol. 9, no. 2, pp. 216–238, 2017.

[18] F. Bella, "Driving simulator for speed research on two-lane rural roads," *Accident Analysis & Prevention*, vol. 40, no. 3, pp. 1078–1087, 2008.

[19] J. Törnros, "Driving behavior in a real and a simulated road tunnel–a validation study," *Accident Analysis & Prevention*, vol. 30, no. 4, pp. 497–503, 1998.

[20] A. Calvi and F. D'Amico, "A study of the effects of road tunnel on driver behavior and road safety using driving simulator," *Advances in Transportation Studies*, 2013.

[21] E. Ronchi, D. Nilsson, S. Kojić et al., "A Virtual Reality Experiment on Flashing Lights at Emergency Exit Portals for Road Tunnel Evacuation," *Fire Technology*, vol. 52, no. 3, pp. 623–647, 2016.

[22] X. Jia, M. Li, and J. Li, "Study on Effects of Safety Facilities on driver's Speed Perception and Concentration in Expressway Tunnel," *Journal of Residuals Science & Technology*, vol. 17, no. 7, pp. 139.1-139.5, 2016.

[23] H. Wan, Z. Du, B. Ran, and M. Wang, "Speed control method for highway tunnel safety based on visual illusion," *Transportation Research Record Journal of the Transportation Research Board*, vol. 2485, pp. 1–7, 2015.

[24] Y. Dai, C. An, and Z. Liao, "Characteristics of Highway Tunnel accidents," *Computer and Communications*, vol. 28, no. 2, pp. 101–106, 2010.

[25] S. Yasmin, N. Eluru, C. R. Bhat, and R. Tay, "A latent segmentation based generalized ordered logit model to examine factors influencing driver injury severity," *Analytic Methods in Accident Research*, vol. 1, pp. 23–38, 2014.

[26] C. S. Duncan, A. J. Khattak, and F. M. Council, "Applying the ordered probit model to injury severity in truck-passenger car rear-end collisions," *Transportation Research Record Journal of the Transportation Research Board*, vol. 1635, no. 1, pp. 63–71, 1998.

[27] J. S. Long, "Regression models for categorical and limited dependent variables," *Technometrics*, vol. 40, no. 1, pp. 80-81, 2006.

[28] A. Schreiner, P. Bergmans, P. Cherubin et al., "Effects of Drivers' Actions on Severity of Emergency Vehicle Collisions," *Transportation Research Record Journal of the Transportation Research Board*, vol. 2318, no. 1, pp. 90–97, 2018.

[29] S. Anowar, S. Yasmin, and R. Tay, "Factors Influencing the Severity of Intersection Crashes in Bangladesh," *Asian Transport Studies*, vol. 3, no. 2, pp. 1–12, 2014.

[30] B. G. Witmer and P. B. Kline, "Judging perceived and traversed distance in virtual environments," *Presence*, vol. 7, no. 2, pp. 144–167, 1998.

[31] S. Li-Ming and S. Yang, "The theoretical research on traffic noise in highway tunnels," in *Proceedings of the 2011 IEEE 3rd International Conference on Communication Software and Networks*, pp. 746–749, IEEE, 2011.

[32] L. N. Yang and B. M. Shield, "Development of a ray tracing computer model for the prediction of the sound field in long enclosures," *Journal of Sound and Vibration*, vol. 229, no. 1, pp. 133–146, 2000.

[33] Z. Sun and I. F. Akyildiz, "Channel modeling of wireless networks in tunnels," in *Proceedings of the IEEE GLOBECOM 2008 - 2008 IEEE Global Telecommunications Conference*, pp. 158–162, IEEE, 2008.

[34] Z. Sun and I. F. Akyildiz, "Channel modeling and analysis for wireless networks in underground mines and road tunnels," *IEEE Transactions on Communications*, vol. 58, no. 6, pp. 1758–1768, 2010.