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Analysis of the Effect of Tunnel Safety Measures on Vehicle Speed Based on the Analytic Hierarchy Process

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ABSTRACT

The highway tunnel plays a critical role in highway traffic flow, yet its sections are particularly susceptible to traffic accidents. The research shows that the safety measures in the tunnel have a certain effect on improving the safety in the tunnel, but there is a lack of evaluation methods for the use effect of safety measures in the tunnel. To study the application effect of safety measures in tunnels (mainly strobe lights and information boards), this paper takes the driver's subjective feelings and vehicle speed changes as indicators to evaluate the application effect of safety facilities. The Xingshuliang Tunnel in Shaanxi Province, which has been operated and meets the test standards, is used as the test site, and the driver between the Yaozhou and Huangling sections is randomly selected as the test object for data collection. Subjective feelings are mainly obtained by social survey methods to obtain data samples, and the driving speed is collected by NC2000, non-contact five-wheel instrument, video recorder and other equipment. The statistical analysis method is used to study the driving speed of each section inside and outside the tunnel and the driver's response. According to the changing trend of speed, the weight of each test section is calculated by the combination of analytic hierarchy process and quantitative statistical method, and the comprehensive influence degree of safety measures is evaluated. The results show that both the strobe light and the information board induce the driver to reduce the driving speed by 3.1%, which can effectively reduce the driving speed. The strobe light mainly acts on the tunnel entrance and the inside of the tunnel, with a maximum influence range of 205 m. The information board has the greatest effect at the tunnel entrance, with a maximum influence range of 200 m. The above results provide a useful reference for the arrangement of safety measures and put forward the arrangement method of tunnel safety measures in combination with the conclusion, to help improve the safety of the driving environment in the tunnel.

KEYWORDS

highway tunnel; safety measures; subjective feelings; social survey methods; analytic hierarchy process.

1. INTRODUCTION

Highway tunnels play a crucial role in facilitating highway traffic, but they also pose a significant risk for traffic accidents [1–3]. Extensive research has demonstrated that speed is a major contributing factor to these accidents [4–8]. For instance, statistics from the U.S. Highway Traffic Safety Agency reveal that approximately 30% of annual deaths in the United States can be attributed to speeding [9]. In Australian studies, it has been observed that when the speed exceeds 60 km/h, the accident rate doubles with every 5 km/h increase in speed, and the severity of accidents also escalates exponentially [10, 11]. As a hotspot for traffic safety incidents, the tunnel underscores the criticality of speed regulation within its confines. Moreover, in contrast to open roads, highway tunnels feature relatively enclosed driving environments with dim lighting and narrow lanes, factors that can induce stress and tension among drivers [12, 13]. The monotonous tunnel environment may lack the stimulation necessary to keep drivers alert, potentially resulting in driver fatigue, delayed responses and consequently, traffic accidents [14, 15]. Safety measures within tunnels impact tunnel speed, thereby influencing tunnel safety.

The relevant investigation report shows that the driver's tunnel driving safety awareness is lacking. They do not know the various tunnel facilities in the tunnel and believe that there is no difference between driving in the tunnel and driving on the open road, and they tend to ignore the control signal [16, 17]. In addition, the accident rate in the tunnel is significantly higher than that in the open road, and the accident rate in different tunnel areas is also different [18, 19]. Therefore, perfect traffic safety facilities are very important to improve the safety of highway tunnels and prevent traffic accidents [20–25]. In highway sections, strobe lights and LED information boards are often used to prompt information in front of the tunnel to effectively remind drivers of safety precautions. These measures are extensively utilised in highway tunnel sections in China, and their arrangement is depicted in *Figure 1*. Jinliang Xu [26], through questionnaire surveys and field experiments, investigated the impact of LED information boards, strobe lights, human-voice broadcasts and siren broadcasts on driving safety. The survey results indicated that all facilities, except for human-voice broadcasts, were perceived to enhance driving safety. Haipeng Zhang et al. [27] studied the factors that may affect the effectiveness of the use of safety measures to help the scientific setting of highway traffic safety facilities.

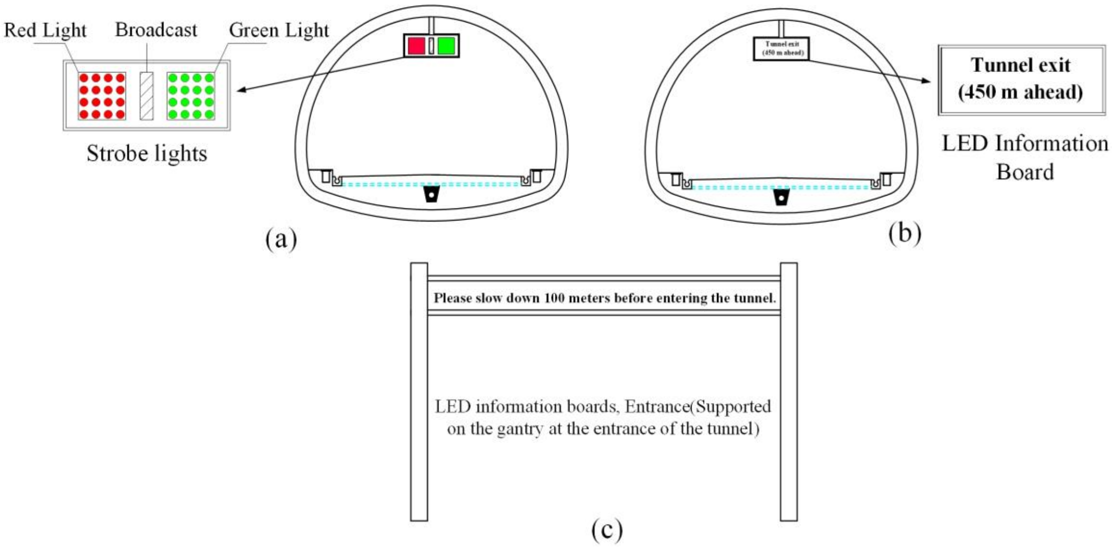


Figure 1 – Layout diagram of strobe lights and LED information board in tunnel test

Additionally, there is limited research conducted by scholars on evaluating the effectiveness of safety measures implemented in tunnels. Hong Tang [28] defined the concept of evaluating road traffic safety measures and established a theoretical framework by integrating both domestic and international safety evaluation systems, thus supporting the development of safety measures in China. Wenbin Zhang [29] analysed the causes of traffic accidents in tunnels and proposed reducing accidents through speed reduction. By utilising the theory of audio-visual perception and a computer-based simulation, parameters in the model were determined to evaluate the impact of traffic safety measures on speed reduction. Jianjun Wang et al. [30] examined the application status of traffic safety facilities in China's expressway network and devised principles and methods for planning safety measures in the road network. To address accidents resulting from inadequate implementation of previous planning schemes, a post-evaluation method combining accident statistical analysis and expert experience was proposed to guide the rational application of safety measures in the expressway network. Consequently, there is a need to establish evaluation models to assess the extent of control exerted by tunnel safety measures on vehicle speed and overall safety.

To address the aforementioned safety concerns within tunnels and investigate the effectiveness of safety measures on vehicle speed modulation, this study employs drivers' subjective perceptions and changes in vehicle speed as key metrics for evaluating safety facility effectiveness. The Xingshuliang Tunnel in Shaanxi Province serves as the experimental site, with drivers randomly selected from the Yaozhou to Huangling sections for data collection. Subjective perceptions are primarily obtained through social survey methods to gather data samples while driving speeds are recorded using equipment such as NC2000, a non-contact five-wheel instrument, and video recorders. Statistical analysis methods are then applied to examine driving speeds within and outside the tunnel and drivers' responses. The weights of each test section are determined by combining the analytic hierarchy process with quantitative statistical methods to assess the comprehensive impact of safety measures.

2. EXPERIMENTAL METHODS

2.1 General

This section primarily introduces the methodology for obtaining experimental data. To investigate the impact of safety measures in highway tunnels on driving speed, crucial safety measures are initially identified. The collected sample data in this study are primarily categorised into two aspects: the subjective perception of the driver and their speed control capabilities. The driver's subjective feelings are gathered through social survey techniques, while the measurement of driving speed is obtained through a combination of a five-wheel instrument and video recording during field experiments.

2.2 Selection of safety measures

Through an extensive investigation and study of several mountainous expressways in Shaanxi Province, China, including Xi'an to Hanzhong, Xi'an to Ankang, Xi'an to Yulin and Baoji to Hanzhong, this research has identified specific visual warning facilities, such as strobe lights, LED information boards, and contour markers as illustrated in *Figure 1*. Additionally, auditory warning measures, such as cable broadcasting, have also been selected.

2.3 Questionnaire survey

The test site chosen is the Xingshuliang Tunnel in Shaanxi Province, which, as a typical tunnel, incorporates various safety measures necessary for the experiment. The operational environment is favourable, with stable traffic volume and minimal occurrences of congestion. The tunnel features a comprehensive range of safety facilities that are representative and compliant with test standards, making it an ideal selection for the study. The drivers travelling between the Yaozhou and Huangling sections were randomly chosen as the participants for data collection. Questionnaires were distributed to vehicle drivers and occupants who held a valid driver's licence. The primary focus when designing the questionnaire was to assess whether various safety measures contribute to enhancing drivers' attention and alertness. The questionnaire encompassed the driver's basic information (e.g. name, age, gender), driving-related details (e.g. driving experience) and the perception of safety measures. The perception of safety measures would subsequently be utilised for data analysis. In the questionnaire, different safety measures were represented by letters *A–E*, while numbers 1–2 indicated the driver's recognition of the effectiveness of each safety measure (e.g. '1' denoted helpful, '0' denoted not helpful).

A total of 436 questionnaires were collected during the experiment. Using the criterion of whether safety measures have a positive impact, the questionnaire survey encompassed three investigations: attention improvement, vehicle speed control and vehicle distance perception. Given the substantial number of data samples and their high reliability, the median value was chosen as the evaluation index to determine the extent to which it benefited the entire driver sample. If the recognition exceeded 50%, the impact index was deemed beneficial for the overall driver sample; conversely, if the recognition fell below 50%, it was considered to have no significant effect.

Due to the substantial sample size, the data are primarily influenced by the error level and confidence level. The calculation formula for sample size is as *Equation 1*.

$$N = \frac{z^2\sigma^2}{d^2} \tag{1}$$

In the formula, *N* represents the required sample size, *z* is the ‘*z*’ statistic corresponding to the desired confidence level and *σ* denotes the population standard deviation. For this paper, a value of 0.5 is assumed for *σ*. *d* represents half of the confidence interval, which is the acceptable error or survey error in practical application. With a confidence level of 95% and an allowable error of 5%, the calculated sample size is 385. Therefore, this study ensures that the number of questionnaires collected exceeds 385.

The purpose of controlling the sample size is to ensure the accuracy of the driving speed value [31–34]. *Equation 2* can be used to calculate the minimum sample size required for this purpose. In the equation, *n* represents the minimum sample size, *t* represents the confidence level coefficient (typically taken as 1.96 for a 95% confidence level), *σ* represents the standard deviation of vehicle speed (typically taken as 8.5 km/h) and *E* represents the allowable error of vehicle speed measurement (typically set at 2 km/h).

$$n = \left(\frac{t\sigma}{E}\right)^2 \tag{2}$$

Therefore, in order to guarantee the accuracy of the speed measurement, it is necessary to ensure that each group of data has a minimum sample size of at least 68. However, due to limitations in human and material resources, it may not be feasible to obtain samples that satisfy a 95% confidence level and an allowable error of less than 5% for each test condition. In such cases, the traditional sample selection method in statistics can be adopted, as shown in *Equation 3*, where *k* represents the number of variables and *N* represents the number of samples.

$$N \geq (k+1) \tag{3}$$

Considering the composition of traffic on China’s expressways, the ‘2000 National Trunk Highway Traffic Manual’ indicates that small vehicles account for 57.8% of the total traffic, while medium-sized and large vehicles account for 42.2%. To simulate the actual traffic flow when measuring speed, a ratio of 6:4 is used, resulting in a total of 10 groups of samples under each test condition.

2.4 Field test

The environmental changes at the tunnel entrance and exit can significantly impact the driver’s behaviour while driving. External factors such as the condition of the highway, traffic and the surrounding environment greatly influence the driver’s behaviour. For instance, the “black hole” effect at the tunnel entrance has a certain influence on the driver’s behaviour [35]. The driver’s ability to adapt to the external environment directly affects their ability to accurately perceive dynamic information during this period. Inadequate implementation of safety measures not only hampers the driver’s adaptability but also diminishes their attention. To enhance driving safety, drivers should conduct a thorough information search upon entering the tunnel. However, in practice, many drivers rely on their previous experience and mistakenly assume that they have already mastered the information about the road environment, leading to a lack of vigilance when entering the tunnel. The section where the driving speed decreases the most is concentrated within 100 m after entering the tunnel, while the deceleration behaviour is less pronounced and less significant from 200 m before the entrance to the entrance itself. This gradient change in vehicle speed poses a safety risk. In this study, a minimum adaptation time of 0.167 seconds was established for tunnel sections to mitigate the influence of the black-and-white hole phenomenon on the experiments [36].

This paper examines whether the use of strobe lights and LED information boards can improve the driver’s ability to control speed changes. The test plan is listed herein:

— Step 1: Preparation prior to testing entails coordination with tunnel management, procurement of testing instruments, and the allocation of corresponding pile numbers for measurement arrangements within the tunnel.
— Step 2: By analysing subjective feedback from test samples, the efficacy of safety measures is preliminarily assessed, with further investigation into their impact. Additionally, communication with the tunnel’s control room allows for appropriate adjustments to the utilisation of safety measures during testing, ensuring that vehicles are only subjected to these measures under specific test conditions.
— Step 3: Along the inner side of the test section, indicator signs are positioned every 30 meters, utilising small coloured cardboard for visibility to test personnel while minimising distraction to passing drivers.

These indicators serve to assess the constancy of distance from the preceding vehicle, while efforts are made to maintain a safe following distance of 60 meters for driving safety.

— Step 4: Under each test condition, vehicles from the past are randomly chosen for following, with an aim to mimic typical driving behaviours and streamline instrument installation. The car-following range spans from 500 meters prior to the tunnel entrance to 300 meters beyond its exit. Upon selection, the driving recorder initiates operation at 300 meters from the tunnel entry, capturing instantaneous speeds at 3-second intervals. Simultaneously, video recording commences, documenting the following vehicle's behaviour until the conclusion of the trial. To ensure a representative sample size and traffic diversity, a mix of 4 large vehicles and 6 small vehicles is predetermined.

— Step 5: Following each test series, the consistency of car-following behaviour is evaluated by analysing video recordings alongside distance indication signs from the lead vehicle. Successful car-following is deemed achieved if the process adheres to the designated distance indicators; otherwise, supplementary tests are conducted.

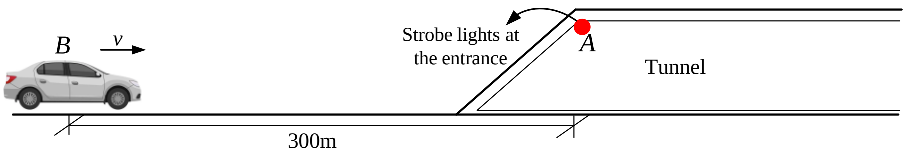
— Step 6: Upon establishing the reliability of car-following data across all test groups, the testing phase concludes, paving the way for indoor data analysis and processing.

Analysis of the influence range of strobe lights at the tunnel entrance

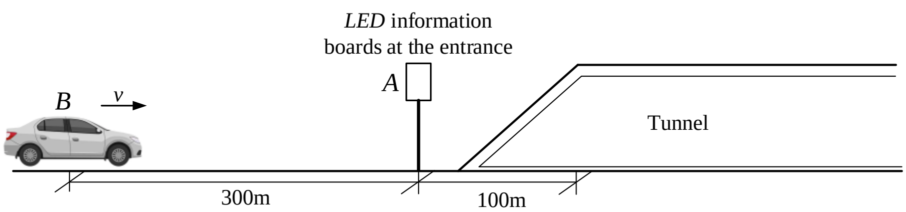
To analyse the influence range of strobe lights on drivers, this paper determines the test range based on the principle of drivers' dynamic vision. When driving at the designed speed of 60 km/h, the driver's fixation point is 300–350 m ahead. It can be assumed that the strobe light is within the driver's field of vision, approximately 300–350 m ahead of the vehicle. Therefore, the data collection and collation section is chosen as the range of 300 m ahead of the first strobe light after entering the tunnel. The relative positions of the strobe lights in the test section (tunnel entrance, tunnel interior, tunnel exit) are illustrated in *Figure 2a*, *Figure 2b* and *Figure 2c*. Point A represents the location of the stroboscopic light, and point B marks the starting point of the test.

Analysis of the influence range of the LED information board at the tunnel entrance

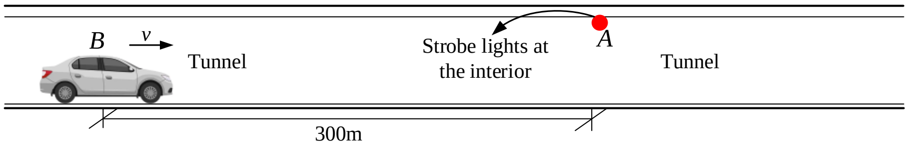
To analyse the influence range of the LED information board on drivers, this paper determines the test range based on the principle of drivers' dynamic vision. When driving at the designed speed of 60 km/h, the driver's fixation point is 300–350 m ahead. It can be assumed that the LED information board is within the driver's field of vision, approximately 300–350 m ahead of the vehicle. Therefore, the data collection and collation section is chosen as the range of 300 m ahead of the first LED information board after entering the tunnel. Additionally, the layout of the LED information board slightly differs from that of the strobe light. In certain cases, it is necessary to provide information regarding lane changes to drivers. To allow drivers sufficient distance to perform lane change manoeuvres, LED information boards are generally placed in front of the tunnel entrance and exit, ensuring drivers can respond after being informed. In the actual test tunnel, the first LED information board within the test range is positioned approximately 100 m from the tunnel entrance, and the nearest LED information board to the exit is located around 450 m from the exit. The relative position diagram of the LED information board in the test section (tunnel entrance, tunnel interior, tunnel exit) is presented in *Figure 2d*, *Figure 2e* and *Figure 2f*, where point A represents the location of the LED information board, and point B denotes the starting point of the test.



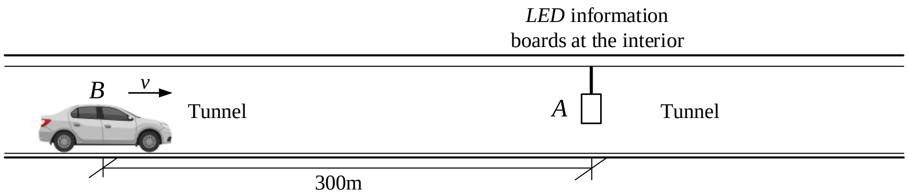
(a) Strobe lights, entrance



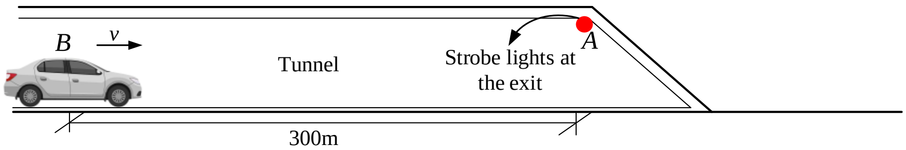
(b) LED information boards, entrance



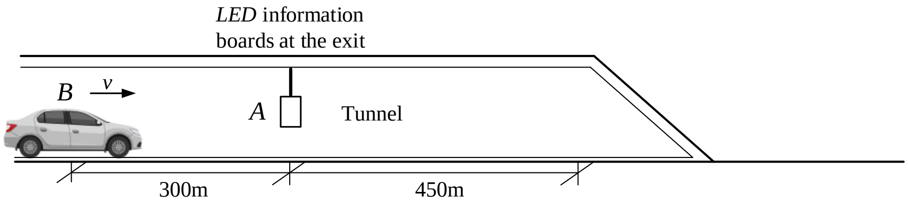
(c) Strobe lights, interior



(d) LED information boards, interior



(e) Strobe lights, exit



(f) LED information boards, exit

Figure 2 – Safety measures arrangement position in field test

3. DATA ANALYSIS METHOD

3.1 General

To investigate the impact of tunnel safety measures on vehicle speed, a statistical analysis method is employed to examine the driving speed within and outside the tunnel, as well as the driver's response. Based on the speed's fluctuation, the weight of each test section is determined through a combination of the analytic hierarchy process and quantitative statistical methods, enabling the assessment of the overall impact of safety measures. When establishing the evaluation system for safety measures, it is important to select appropriate methods to ensure its scientific validity. One commonly used method is the Delphi method, also known as the expert opinion method, which involves gathering opinions from experts in a horizontal manner. However, it should be noted that the results obtained from this method heavily rely on the experts' experience and are subject to certain limitations. On the other hand, the analytic hierarchy process [37–41] is particularly useful for addressing problems that are challenging to be fully quantitatively analysed. Combining subjective and objective elements through the expert method allows for the classification of multiple problems and the simplification of complex issues. Considering these factors, this paper opts to employ the analytic hierarchy process to establish the evaluation system for safety measures.

3.2 Constructing the target hierarchy

The target hierarchy for the components in this study is as follows:

- Target layer: tunnel safety measures.
- Criterion layer: speed change of the vehicle at the entrance of the tunnel under the condition of stroboscopic light, speed change of the vehicle at the entrance of the tunnel under the condition of LED

information board, speed change of the vehicle at the entrance of the tunnel under the condition of cable broadcasting, speed change of the vehicle inside the tunnel under the condition of stroboscopic light, speed change of the vehicle inside the tunnel under the condition of LED information board, speed change of the vehicle inside the tunnel under the condition of cable broadcasting, speed change of the vehicle at the exit of the tunnel under the condition of stroboscopic light, speed change of the vehicle at the exit of the tunnel under the condition of LED information board, and speed change of the vehicle at the exit of the tunnel under the condition of cable broadcasting.

— Scheme layer: strobe lights, LED information board, cable radio.

3.3 Define the scale table and construct the index comparison table

The evaluation standard for this study is the percentage of speed reduction. The strength of the evaluation is divided into three parts: the whole process of the test, the entrance and exit of the tunnel and the inside of the tunnel. It is important to note that the speed of the driver at the exit of the tunnel shows a different pattern compared to the entrance and inside of the tunnel. Therefore, the evaluation of the use effect does not consider the speed change at the exit. When evaluating the use effect of the strobe light, it is necessary to consider not only the effectiveness reflected by the change in overall driving speed but also the effectiveness reflected by the local change in the inlet and internal speed. This requires the distribution of weight coefficients. In this paper, the weight selection method combines the analytic hierarchy process and quantitative statistical method.

Weight of strobe light

A strobe light safety evaluation set U is established. Considering that the speed is a single data calculated based on the inlet speed and the internal speed, it is evaluated from both the overall and local aspects. The set is denoted as $U=\{U_1, U_2\}$, and the relative weights of U_1 and U_2 are both 0.5. U_1 represents the effectiveness reflected by the change in driving speed, while $U_2=\{U_{21}, U_{22}\}$. U_{21} represents the effectiveness reflected by the change in inlet speed, and U_{22} represents the effectiveness reflected by the change in internal speed. The weights of U_{21} and U_{22} are calculated as follows.

Table 1 displays the percentage of sample data in the U_{21} and U_{22} factor sets for each degree of influence. The evaluation set $V=\{V_1, V_2, V_3, V_4\}$={ineffective, low, medium, high} is established.

Table 1 – Effectiveness evaluation results of strobe lights

Index	**Effectiveness evaluation**			
	Ineffective	low	middle	high
Effectiveness at the entrance	0%	0%	40%	60%
Internal effectiveness	40%	10%	20%	30%

For the assignment of ineffective, low, medium and high, only the data with low and above assignments are selected for statistics. The weights of these three options are 0.22, 0.33; 0.45, respectively. Therefore, U_2=(0.6432, 0.3568).

LED information board weight

An LED information board safety evaluation set B is established. Similar to the strobe light evaluation, the driving speed is evaluated from both the overall and local aspects. The set is denoted as $B=\{B_1, U_2\}$, and the relative weights of B_1 and B_2 are both 0.5. B_1 represents the effectiveness reflected by the change in driving speed, while $B_2=\{B_{21}, B_{22}\}$. B_{21} represents the effectiveness reflected by the change in inlet speed, and B_{22} represents the effectiveness reflected by the change in internal speed. The weights of B_{21} and B_{22} are calculated as follows.

Table 2 shows the percentage of sample data in the B_{21} and B_{22} factors for each degree of influence. The evaluation set $V=\{V_1, V_2, V_3, V_4\}$ = {ineffective, low, medium, high} is established.

Table 2 – Effectiveness evaluation results of LED information board

Index	Effectiveness evaluation			
	Ineffective	**low**	**middle**	**high**
Effectiveness at the entrance	0%	20%	10%	70%
Internal effectiveness	80%	20%	0%	0%

For the assignment of ineffective, low, medium and high, only the data with low and above assignments are selected for statistics. The weights of these three options are 0.22, 0.33; 0.45, respectively. Therefore, B=(0.8991,0.1009).

Limited broadcast weight

An LED information board safety evaluation set C is established. Similar to the previous evaluations, the driving speed is evaluated from both the overall and local aspects. The set is denoted as $C=\{C_1, U_2\}$, and the relative weights of C_1 and C_2 are both 0.5. C_1 represents the effectiveness reflected by the change in driving speed, while $C_2=\{C_{21}, C_{22}\}$. C_{21} represents the effectiveness reflected by the change in inlet speed, and C_{22} represents the effectiveness reflected by the change in internal speed. The weights of C_{21} and C_{22} are calculated as follows.

Table 3 shows the percentage of sample data in the C_{21} and C_{22} factor sets for each degree of influence. The evaluation set $V=\{V_1, V_2, V_3, V_4\}$={ineffective, low, medium, high} is established.

Table 3 – Effectiveness evaluation results of wire broadcasting

Index	Effectiveness evaluation			
	Ineffective	**low**	**middle**	**high**
Effectiveness at the entrance	0%	10%	30%	60%
Internal effectiveness	90%	10%	0%	0%

For the assignment of ineffective, low, medium and high, only the data with low and above assignments are selected for statistics. The weights of these three options are 0.22, 0.33; 0.45, respectively. Therefore, C=(0.9467,0.5323).

Consistency test gives weight

The P-C judgment matrix for the scheme layer and criterion layer is constructed as follows: $P_i \rightarrow C_j$ (i=1, 2...18; j=1, 2...6). Specifically, $P_i \rightarrow C_1$ (i=1,2,3,4) represents the judgment matrix for the professional ability of schemes 1 to 4. $P_i \rightarrow C_2$ (i=5, 6, 7) represents the judgment matrix for the professional ability of schemes 5 to 7. $P_i \rightarrow C_3$ (i=8, 9, 10) represents the judgment matrix for the professional ability of schemes 8, 9 and 10. $P_i \rightarrow C_4$ (i=11, 12, 13) represents the judgement matrix for the professional ability of schemes 11 to 13. $P_i \rightarrow C_5$ (i=14, 15, 16) represents the judgement matrix for the professional ability of schemes 14 to 16. $P_i \rightarrow C_6$ (i=17, 18) represents the judgement matrix for the professional ability of schemes 17 to 18.

The consistency test was conducted using Matlab as described in *Equation 4*. The test involved inputting each judgement matrix into Matlab and checking if the values were less than 0.1, as stipulated for passing the consistency test.

$$CI = \frac{\lambda_{\max} - n}{n-1}, CR = \frac{CI}{RI} \tag{4}$$

where $\lambda_{\max}$ is the maximum eigenvalue of the comparison matrix of the model, n is the order of the matrix, CI is the consistency index, CR is the consistency ratio, and RI is the random consistency index.

Weights were calculated at all levels. The calculation results of the arithmetic average method, geometric average method and maximum eigenvalue method were compared. This paper utilised the maximum eigenvalue method and Matlab software to perform the aforementioned operations on the recovered questionnaire results, and the average value was calculated. The total weight was then calculated. The weight vector of the criterion layer *C* relative to the target layer *M* is represented by $w=(w_1, w_2, w_3, w_4, w_5, w_6)^T$, and the weight vector of the scheme layer *i* relative to the corresponding criterion layer index is represented by p_{ij}. The combined weight of the scheme layer to the target layer is denoted as $L_j=P_{ij}w_j$.

Combined with the tunnel access in Sections 3.3.1, 3.3.2 and 3.3.3, as well as the impact of tunnel conditions on speed, this study examines speed variations at these locations and the effects of strobe lights and LED information boards on speed.

4. RESULTS AND DISCUSSION

4.1 Questionnaire survey

The analysis of the survey results regarding various safety measures is depicted in *Figure 3* with the questionnaire variables summarised in *Table 4*. The figure illustrates that strobe lights, LED information boards, cable broadcasts and contour marks are all beneficial to the driver's safe driving. In the subsequent analysis, the primary focus is on the two safety measures of LED information boards and strobe lights.

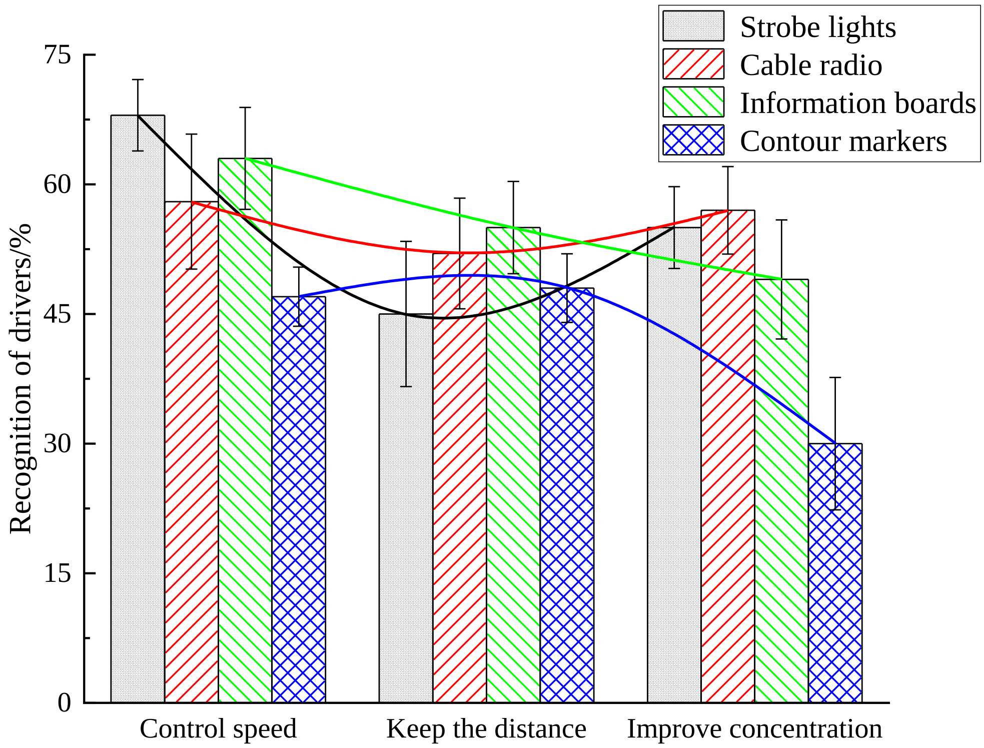


Figure 3 – The recognition of the four types of safety measures by drivers of tunnel safety

Table 4 – Questionnaire variables (%)

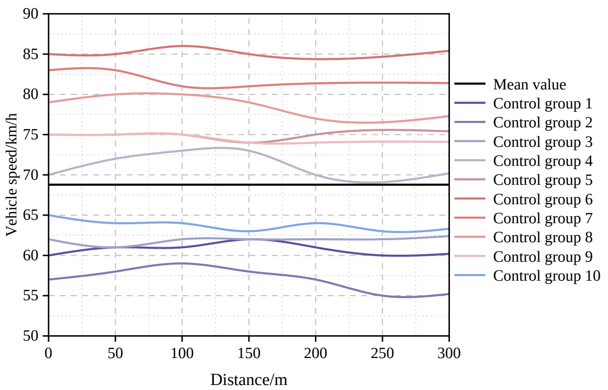
Index	Control speed	Keep the distance	Improve concentration	Mean	SD
Strobe lights	68	45	55	56.0	11.53
Cable radio	58	52	57	55.7	3.21
Information boards	63	55	49	55.7	7.02
Contour markers	47	48	30	41.7	10.11

From *Figure 3*, it is evident that the influence of different safety measures on drivers is not entirely consistent, as each safety measure possesses distinct effects and characteristics. For instance, based on the survey results, strobe lights demonstrate the most pronounced effect on controlling vehicle speed, surpassing other safety measures. However, they have minimal impact on reminding drivers to maintain a safe distance. More than half of the surveyed drivers believe that strobe lights do not aid them in maintaining a safe distance. On the other hand, the other three safety measures outperform strobe lights in reminding drivers to keep a safe distance, despite most drivers perceiving this assistance as minimal. The LED information board, recognised as the safety measure with the greatest subjective impact according to the survey, is acknowledged by drivers for its impact in all aspects, although it does not stand out in a specific category and exhibits a relatively even distribution. Therefore, evaluating its impact more precisely and scientifically necessitates an assessment of changes in driving speed.

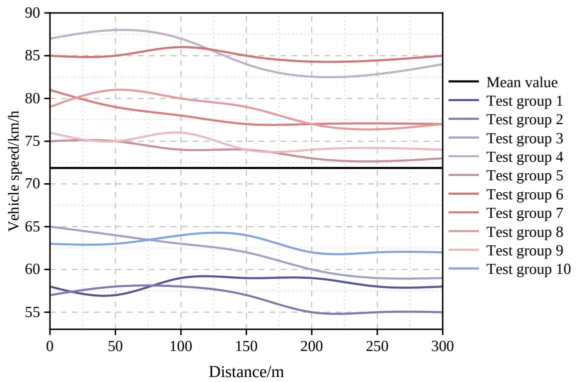
4.2 Field test

Performance of strobe lights

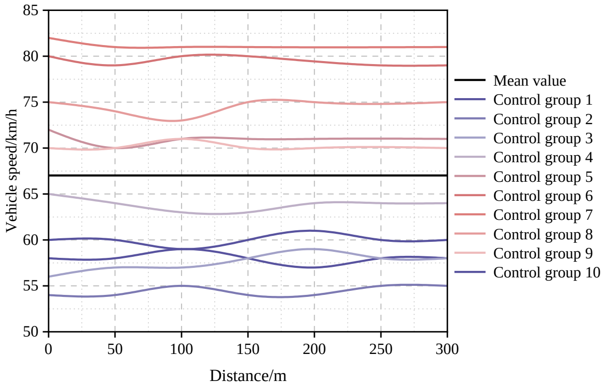
It is evident that drivers adjust their speeds based on the distance between their vehicle and the tunnel entrance. As the distance from the tunnel entrance decreases, the vehicle's speed decreases, as shown in the speed mean curve in *Figures 4a and 4b*. To further validate the accuracy of the stroboscopic light's influence range in the tunnel entrance section, this study analyses the position where the vehicle speed of each test group begins to decrease for comparative analysis. The results indicate that the average speed curve of the two test groups begins to decline 200 meters away from point *A*. However, the mean curve only provides an overall trend. In order to assess the impact of strobe lights on individual drivers, the speed change point for each subject is analysed. When the strobe lights are turned on, all subjects exhibit deceleration behaviour. The majority of drivers start to slow down 100 meters before the strobe lights, while a few drivers begin to decelerate 50 meters before the strobe lights. When the stroboscopic light is not enabled, two drivers do not exhibit deceleration behaviour, and the distribution of speed change points varies significantly. Most drivers decelerate between 50 to 100 meters. After selecting the speed reduction point for each tested individual, the average result is as follows: when the stroboscopic light is enabled, the driver's deceleration point is 155 meters from point *A*, whereas when it is not turned on, the distance from point *A* is slightly closer at 135 meters. This result demonstrates that the overall average speed change does not accurately reflect the effect of strobe lights. It is believed that the tunnel environment near the tunnel entrance when strobe lights are not enabled, may lead to driver misjudgement of speed and more frequent speed changes. In summary, the strobe light does not significantly improve the driver's deceleration range, but individual data indicates that the strobe light does help maintain a steady speed change before the driver enters the tunnel and expands the deceleration range for some individuals, advancing the deceleration behaviour by approximately 20 meters.



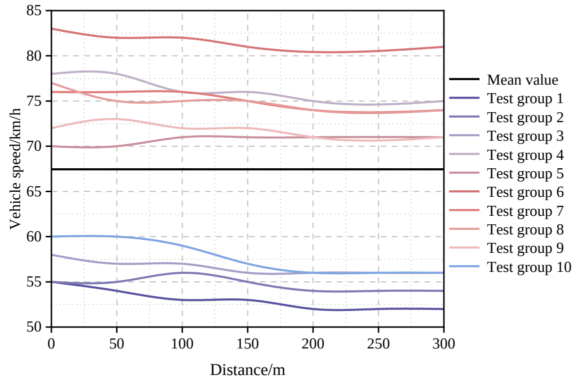
(a) Entrance, control group



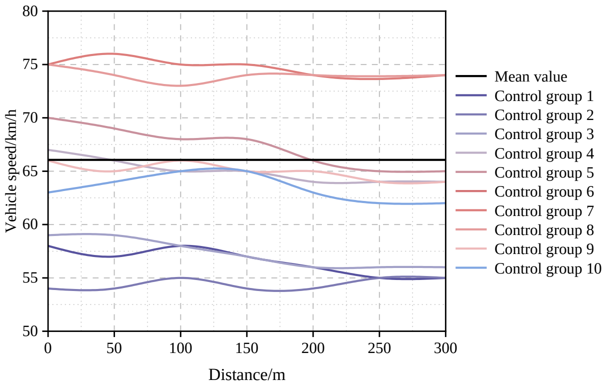
(b) Entrance, test group



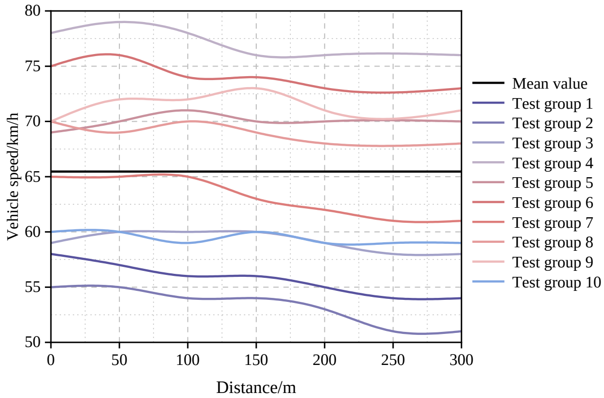
(c) Interior, control group



(d) Interior, test group



(e) Exit, control group



(f) Exit, test group

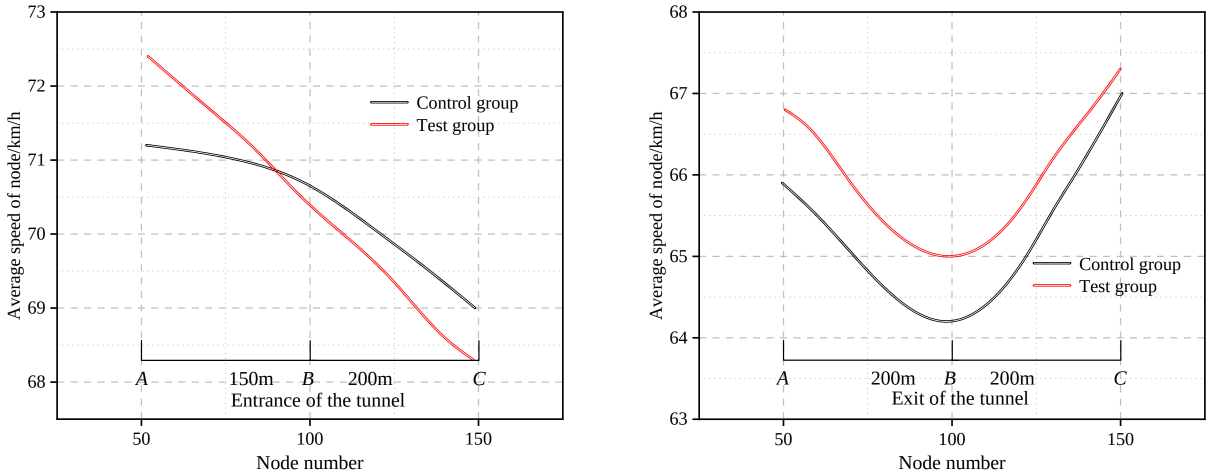
Figure 4 – Speed change diagram under strobe lights

Inside the tunnel, the change in driving speed is not as pronounced as at the entrance. When the strobe light is not enabled, the change in driving speed is not significant. However, when the strobe light is enabled, the speed of the vehicle decreases as it approaches the tunnel entrance, as shown in the average speed curve in *Figures 4c and 4d*. To further validate the accuracy of the strobe light's influence range inside the tunnel, this study analyses the position where the speed of each test group decreases for comparative analysis. The position where the speed mean curve begins to decline, when the strobe light is enabled, is 250 meters away from point *A*, while the speed mean curve fluctuates when the strobe light is not enabled. However, the mean curve only represents the overall trend. To assess the impact of strobe lights on individual drivers, the speed change point for each subject is analysed. When the strobe lights are enabled, 80% of the subjects exhibit deceleration behaviour, with the driver's deceleration occurring 150 meters away from the strobe lights. When the strobe lights are not enabled, the change in vehicle speed is irregular. After selecting the speed reduction point for each tested individual, the average result is as follows: when the strobe light is enabled, the driver's deceleration point is 205 meters away from point *A*. Inside the tunnel, both from an overall and individual perspective, the strobe light helps improve the driver's deceleration range.

Most drivers adopt different speeds as the distance between the vehicle and the tunnel exit changes. The vehicle's speed decreases as the distance from the tunnel exit approaches, as reflected in the average speed curve in *Figures 4e and 4f*. This phenomenon is similar to the change in driving speed at the tunnel entrance and confirms that the "black hole" and "white hole" visually affect the driver's driving behaviour. To further validate the accuracy of the strobe light's influence range at the tunnel entrance section, we selected the position where the average speed of each test group decreased for comparative analysis and found that the position where the average speed curve of the two test groups began to decline was different. When the strobe light is turned on, the driver's deceleration behaviour occurs relatively early, starting to decelerate 250 meters from point *A*, while without turning on the strobe light, the distance is 200 meters from point *A*. However, the mean curve only represents the overall trend. To assess the impact of strobe lights on individual drivers, the speed change point for each subject is analysed. When the strobe lights are turned on, all subjects exhibit deceleration behaviour. The majority of drivers begin to slow down 150 meters before the strobe lights. When the stroboscopic light is not enabled, two drivers do not exhibit deceleration behaviour, and the change in vehicle speed fluctuates greatly. Most drivers decelerate between 50 to 150 meters. After selecting the speed reduction point for each tested individual, the average result is as follows: when the strobe light is enabled, the driver's deceleration point is 205 meters away from point *A*, while when it is not turned on, it is slightly closer to point *A* at 180 meters.

The average speed change point is selected as the initial point for dividing the test interval, and the change in speed after the activation of the strobe light is examined. Three points, ranging from 150 m before the tunnel entrance to 200 m after entering the tunnel, are chosen to analyse the speed variation. The node speed represents the average speed of 10 groups of testers. As depicted in *Figure 5a*, the control group exhibits a speed drop ratio of 0.7% between node 1 and node 2 and a speed drop of 2.5% between node 2 and node 3. Consequently, it is postulated that the driver's deceleration behaviour, triggered by environmental changes, predominantly occurs inside the tunnel, aligning with the observation that deceleration behaviour primarily transpires within the tunnel. In the stroboscopic light test group, the speed between nodes 1 and 2 experienced a decrease of 2.6%, and the speed between nodes 2 and 3 decreased by 3.3%. Although the speed drop ratio inside the tunnel remained higher than that outside the tunnel, it is evident that the activation of the strobe light prompted the driver to complete the deceleration process to some extent before entering the tunnel, rendering the entire deceleration process more gradual. Furthermore, within the entire test section, the speed drop after turning on the strobe light was higher.

Similar research findings pertain to the exit of the tunnel. Generally, the speed adjustment from 200 m before the exit to 50 m after the exit mainly involves speed reduction, followed by a subsequent increase in speed. Concurrently, based on the driver's dynamic vision, the three-point speed variation from 200 m before the tunnel to 200 m after the tunnel exit is employed to evaluate the efficacy of the strobe light at the entrance and exit of the tunnel, as illustrated in *Figure 5b* below.



(a) Entrance, strobe lights *(b) Exit, strobe lights*

Figure 5 – Average speed change diagram of node (strobe lights)

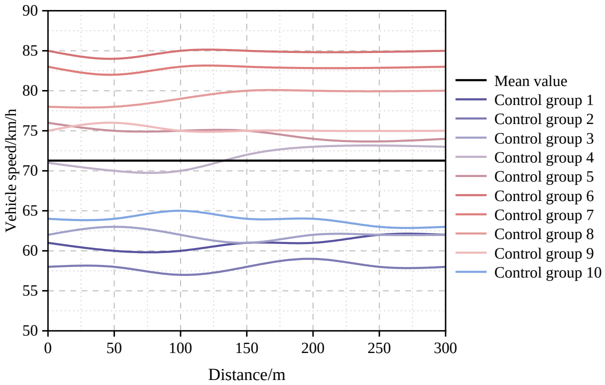
At the tunnel exit, the curve trend for both test conditions is comparable. The control group and the stroboscopic light test group exhibit a similar proportion of speed decrease between node 1 and node 2, which aligns with the aforementioned observation. It can be inferred that the impact of the strobe light on the driver at the tunnel exit is minimal.

The flickering characteristics of the strobe light can capture the driver's attention, enhance alertness and facilitate response to the specific driving environment within the tunnel. To analyse its effect on vehicle speed, the average influence range of strobe lights within the tunnel, estimated to be 205 m, is taken into consideration. The vehicle speed from 205 m to point *A* is selected to examine the efficacy of strobe lights within the tunnel.

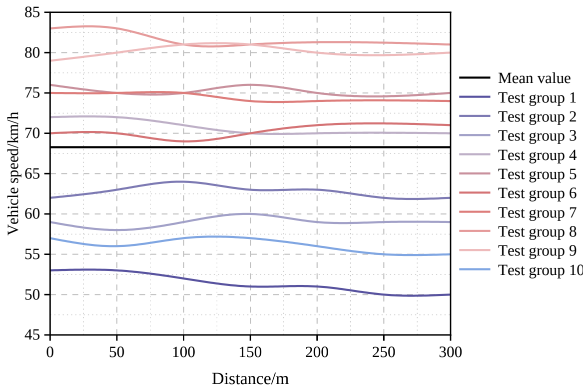
Upon analysing the data from this section, it is observed that the speed of the control group did not decrease; instead, there was a slight increase of 0.7%. This finding aligns with the previously mentioned conclusion that the driver tends to accelerate the vehicle after entering the tunnel for a while. Conversely, when the strobe light was activated, the vehicle speed decreased by 2% within the influence range of the strobe light. Hence, it is deemed that the strobe light's effectiveness contributes to enhancing driving safety to a certain extent.

Performance of LED information board

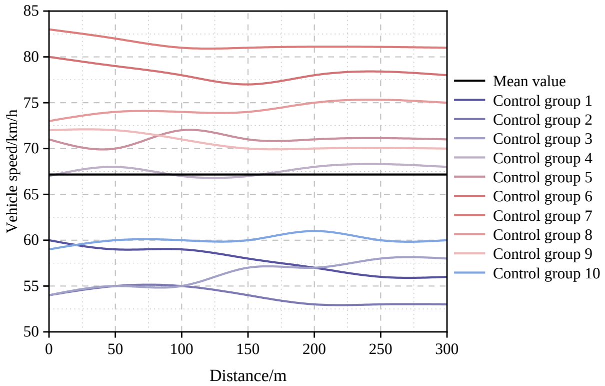
The arrangement of the LED information board differs from that of the strobe light. At 100 meters outside the tunnel entrance, there is no obvious downward trend in the front section of the test section, but as the tunnel entrance approaches, there is deceleration behaviour in the range of approximately 150 meters near the tunnel entrance. The vehicle's speed decreases as it approaches the tunnel entrance, as reflected in the average speed curve in *Figures 6a and 6b*. To further validate the accuracy of the influence range of the LED information board in the tunnel entrance section, we selected the position where the speed of each test group decreased for comparative analysis. It was found that the position where the mean curve began to decline when the LED information board was enabled was 200 meters in front of the LED information board. When the LED information board was not enabled, it was approximately 75 meters in front of the LED information board or 175 meters from the tunnel entrance. This deceleration starting point is similar to the 200 meters in the strobe test group, indicating that both groups of tests are credible. The mean curve only represents the overall trend. To assess the effect of the LED information board on the range between different individuals, the speed change point for each subject is analysed. When the LED information board is enabled, only one driver does not exhibit deceleration behaviour, and the deceleration behaviour of the other nine subjects occurs outside 150 meters from the LED information board. When the LED information board is not enabled, 10 groups of drivers tested outside 100 meters from the information board do not exhibit deceleration behaviour, and a small number of drivers exhibit deceleration behaviour within 0–100 meters from the LED information board. After selecting the speed reduction point for each subject, the average result is as follows: when the LED information board is enabled, the driver's deceleration point is 200 meters from point *A*, while when it is not turned on, it is slightly closer to point *A* at 135 meters. Based on the above data analysis, the LED information board effectively improves the driver's ability to control speed, expands the deceleration range, and promotes a steady change in speed, contributing to driving safety. The deceleration behaviour can be advanced by more than 70 meters, providing the driver with more time to adjust their state and enhance safety.



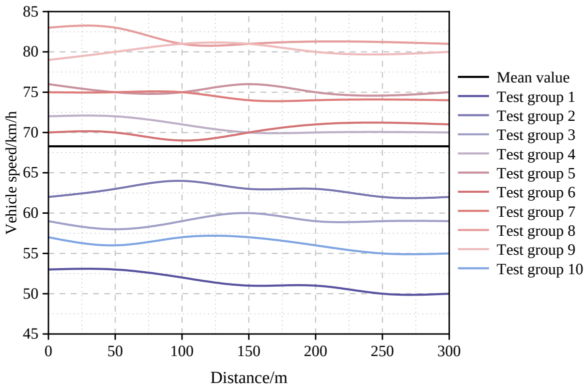
(a) Entrance, control group



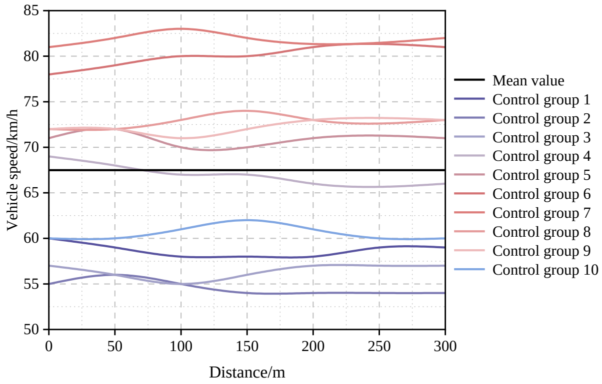
(b) Entrance, test group



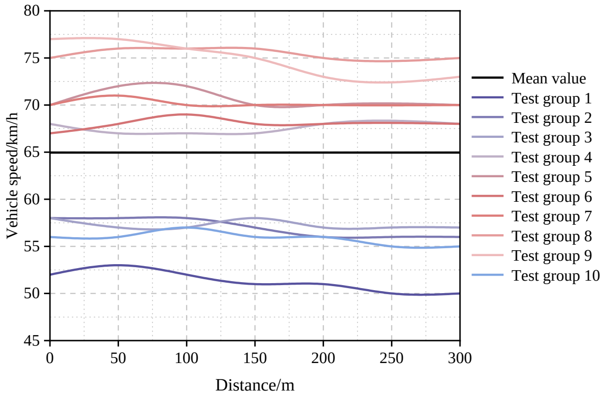
(c) Interior, control group



(d) Interior, test group



(e) Exit, control group



(f) Exit, test group

Figure 6 – Speed change diagram under LED information boards

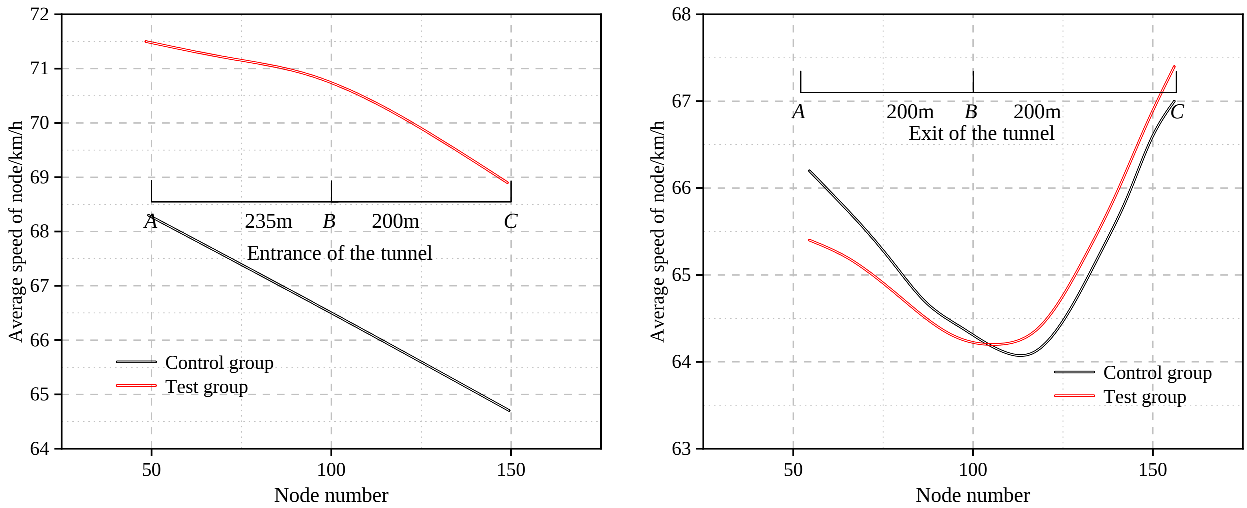
In the tunnel, the change in vehicle speed under the two experimental conditions is not significant relative to the entrance. However, when the LED information board is enabled, there is a slight decrease in driving speed with the approach to the LED information board, as reflected in the average speed curve shown in *Figures 6c and 6d*. To further verify the accuracy of the influence range of the LED information board in the tunnel entrance section, we selected the position where the speed of each test group decreased for comparative analysis and found that the position where the mean curve began to decline under both conditions was 200 m in front of the LED information board. The mean curve only represents the overall trend. To reflect the effect of the LED information board on the range between different individuals, the speed change points of each subject were analysed. When the LED information board was enabled, 80% of the drivers exhibited deceleration behaviour, with most of them reducing speed at a distance of 150 m from the LED information board. However, without opening the LED information board, the speed change showed no obvious regularity, with only half of the drivers reducing speed. After selecting the speed reduction point of each tested person, the average result was as follows: when the LED information board was enabled, the driver's deceleration point was 200 m away from point A. When the LED information board was not enabled, the change in driving speed was irregular. Based on the above data analysis, it can be concluded that while the LED information board does not significantly improve the overall deceleration interval, it does enhance the driver's ability to control speed, expand the deceleration interval, and promote a steady change in speed at the individual level, allowing the driver more time to adjust their state and improve safety.

Due to the differing arrangement of the LED information board compared to the strobe light, both groups of drivers experience similar changes in driving speed approximately 450 m before reaching the tunnel exit. This pattern is evident in the velocity mean curve, as depicted in *Figures 6e and 6f*. To further validate the accuracy of the LED information board's influence range in the tunnel entrance section, the position at which the speed of each test group decreased was selected for comparative analysis. In the absence of the LED information board, the speed change did not exhibit any clustering near point *A*. Only 50% of the tested drivers reduced their driving speed in the test section, and the mean curve began to decline 225 m in front of the LED information board when it was enabled. It is important to note that the mean curve represents the overall trend but to assess the impact of the LED information board on individual drivers, the speed change point of each subject was analysed. When the LED information board was enabled, only one driver did not exhibit deceleration behaviour, while the remaining nine subjects displayed deceleration behaviour occurring beyond 100 m from the LED information board. Conversely, in the absence of the LED information board, half of the drivers did not exhibit any deceleration behaviour. After selecting the speed reduction point for each subject, the mean value was calculated as follows. When the LED information board was enabled, the deceleration point for drivers was located 200 m away from point *A*.

When the safety measures are not activated at the entrance, drivers begin to reduce their speed at an average distance of 235 m from the entrance. Therefore, this study analyses the speed changes at three specific points: 235 m from the tunnel entrance, the tunnel entrance itself and 200 m after entering the tunnel. The average speed of ten test groups is selected for analysis, as shown in *Figure 7a*.

In the control group, the speed reduction ratio between node 1 and node 2 is 1.1% smaller than that between the latter two nodes, and the speed reduction between node 2 and node 3 is 2.5%. Similar to the analysis of strobe lights, the speed changes of drivers in the LED information board condition also align with existing conclusions, indicating that deceleration behaviour mainly occurs inside the tunnel. In the LED information board test group, the speed between nodes 1 and 2 is reduced by 2.6%, and the speed between nodes 2 and 3 is reduced by 2.5%. When the LED information board is enabled, the driver's deceleration behaviour is significantly advanced. Additionally, the deceleration process is relatively evenly distributed, resulting in a smoother driving experience. Therefore, it is believed that the LED information board at the tunnel entrance is helpful in improving driving safety. Generally, the driver's speed decreases before exiting the tunnel due to environmental changes and increases after exiting.

The LED information board closest to the tunnel exit is also located 450 m away from the exit. At this point, it is less influenced by changes in the external environment. Hence, the study selects three points: 300 m before the tunnel exit, the tunnel exit itself and 200 m after the tunnel exit, in order to cover the largest possible area and examine the change in vehicle speed. This serves as a basis for evaluating the effectiveness of the LED information board at the tunnel exit, as shown in *Figure 7b*.



(a) Entrance, LED information boards

(b) Exit, LED information boards

Figure 7 – Average speed change diagram of node (LED information boards)

At the tunnel exit, under the condition of the LED information board test, the change in vehicle speed during the driving process from the tunnel to the exit is smaller than that of the control group. Furthermore, the recovery of vehicle speed is faster, enabling the driver to better adapt to the changing driving environment, anticipate the road ahead and adjust their speed accordingly.

The LED information board enhances driver attention through various slogans and timely transmission of traffic information, thereby improving safety. To analyse its effect on vehicle speed, the study focuses on the distance from the LED information board to point *A*, a range of 200 m, considering it as the average influence range of the LED information board in the tunnel.

From the calculation steps in the section "Limited Broadcast Weight", the scores of the two modes in the tunnel entrance, tunnel exit and tunnel interior can be obtained, as shown in *Figure 8*. Combined with data analysis, it is observed that the vehicle speed in the control group slightly decreased by 0.3%, which had a limited range and negligible impact on traffic safety. When the LED information board was activated, the decrease was slightly more pronounced than in the control group, amounting to 1%. This suggests that the warning effect of the LED information board in the middle section of the tunnel is minimal, and it is challenging to significantly alter the driver's behaviour solely through slogan text.

Based on the above analysis results, it can be found that the strobe lights and LED information boards at the entrance, interior and exit of the tunnel will prompt drivers to take certain deceleration behaviours to ensure driving safety. However, there are still a few drivers who ignore these traffic safety facilities. Konstantinos Kirytopoulos and Jaeyoung Lee also found similar situations in their corresponding research reports [16,17]. The effect of LED information boards seems to be less pronounced than that of strobe lights, possibly due to the fact that LED information boards only serve as reminders and are not as visually appealing as the warning effect of strobe lights. These two types of traffic safety facilities inside the tunnel have little impact on the driver's driving speed. Drivers often take deceleration measures before entering the tunnel, and a constant speed strategy is usually adopted inside the tunnel, with a low probability of further deceleration. According to research results on vehicle speed and accident risk in Australia [10, 11], the accident rate inside the tunnel should be higher than at the exit and entrance, which is consistent with the research results of Amjad Perveza et al. [18, 19]. Therefore, it is extremely important to take more effective safety measures inside the tunnel.

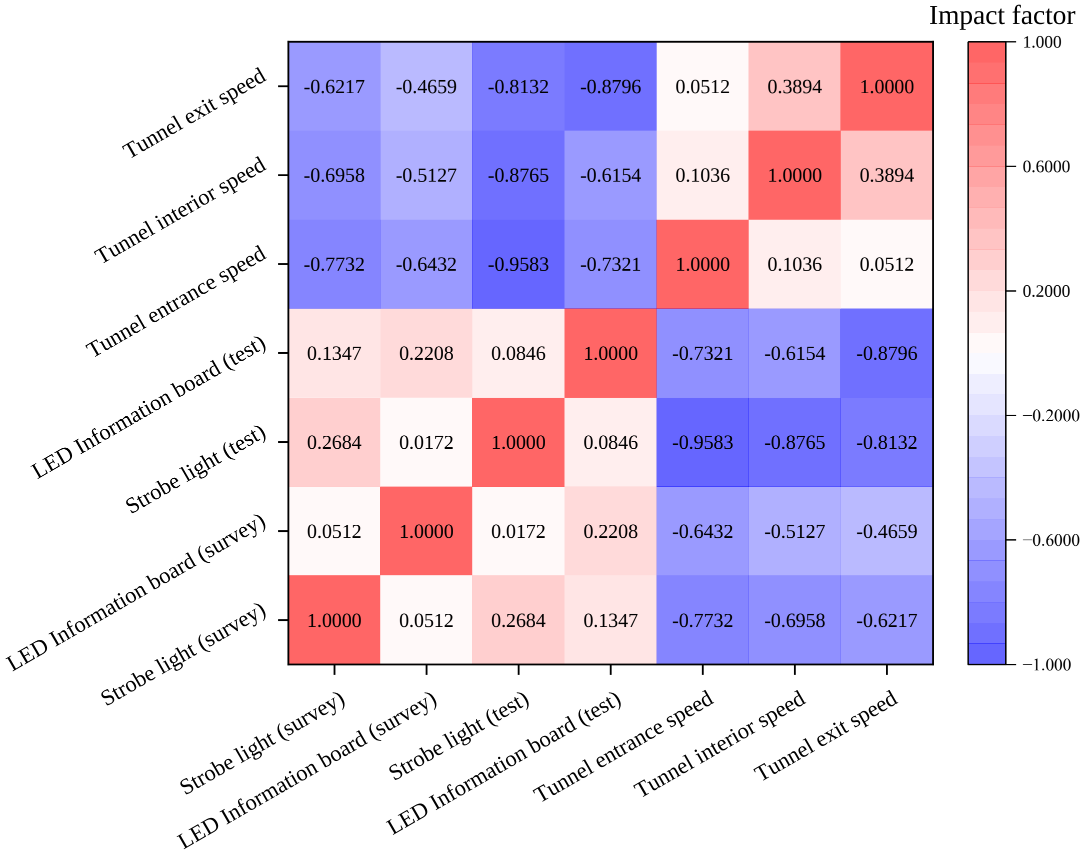


Figure 8 – The impact factor of tunnel safety measures combined with the test position

5. CONCLUSION

In order to investigate the effectiveness of safety measures in tunnels, specifically strobe lights and LED information boards, this study utilises subjective driver perceptions and changes in vehicle speed as indicators for evaluating the impact of these safety facilities. By employing a combination of questionnaire surveys and field tests, the aim is to examine the effectiveness of safety measures in tunnels, with strobe lights and LED information boards being the main focus. The study employs statistical analysis to analyse the driving speed within and outside the tunnel, as well as the drivers' responses. Through the use of the analytic hierarchy process and quantitative statistical methods, the weight of each test section is calculated, and the overall impact of safety measures is assessed. The following are the main findings of this study.

1) Both the strobe light and the LED information board induce the driver to reduce the driving speed by 3.1%, which can effectively reduce the driving speed. The strobe light mainly acts on the tunnel entrance and the inside of the tunnel, with a maximum influence range of 205 m. The LED information board has the greatest effect at the tunnel entrance, with a maximum influence range of 200 m. Within the tunnel, the impact of strobe lights is most conspicuous, followed by informational boards.
2) Decision-makers are advised to implement specific safety measures to mitigate traffic accidents. Regarding the optimal layout method of strobe lights and information boards, the following recommendations are proposed.
   (i) Regarding the placement of strobe lights, given their significant impact on reducing driver speed, it is advised to position them at intervals between the tunnel entrance and interior. Since drivers typically accelerate after traversing 150 m into the tunnel, and the effective range of the strobe light spans approximately 205 m, it is recommended to install a strobe light every 350 m from the tunnel entrance within the general tunnel, thus ensuring drivers maintain a reasonable speed for safe passage.

(ii) Concerning the placement of information boards, their primary function is to prompt drivers to proactively reduce speed, thus mitigating sudden speed reductions. Therefore, it is recommended to primarily situate information boards at locations experiencing significant environmental changes, such as tunnel entrances and exits, while reducing their frequency within the tunnel where their impact is diminished. Analysis indicates an effective range of approximately 200 m near the tunnel entrance. In scenarios where strobe lights are positioned before the tunnel entrance, placing information boards approximately 200 m prior to the tunnel entrance is advised to continually prompt drivers to adjust their speed.

ACKNOWLEDGEMENTS

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