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Study on the Effect of Retro-reflective Properties of Marking Lines on Night-time Driving Safety

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Abstract. Pavement marking is a necessary part of road infrastructure, and its nighttime retroreflective characteristics affect the visibility of the marking and the safety of drivers driving at high speed at night. We selected three highways with different retroreflective coefficients for field driving experiments, extracted the data with Tobii Pro spectacle software and performed analysis of variance; constructed the driving behavior matrix, calculated the weights and eigenvalues with CRITIC assignment method, and quantitatively analyzed the impact of road marking retroreflective performance on night driving safety. The study shows that the retroreflective performance of road markings on Weiqing and Jingtai Expressway meets the requirements of nighttime safe driving; the retroreflective performance of markings on Jinan Bypass Expressway is insufficient, which is a safety hazard for nighttime driving and needs to be maintained in time.

Keywords: pavement markings, retro-reflectivity, night-time driving, driving behavior, eye tracking, traffic safety

1 INTRODUCTION

As a common traffic infrastructure, road marking conveys important information to traffic participants and guides vehicles to drive in a standardized manner. At night, drivers rely on markings to obtain visual cues for safe driving, and the visibility of markings at night is mainly realized by retro-reflection.Relevant studies show that night traffic accident incidence is three times that of daytime[1]. Poor night high-speed driving environment with no road lighting increases accident possibility. Better marking retroreflectivity provides longer visual distance for safer night driving. Currently, few studies on marking retroreflective performance's impact on driving behavior exist, mostly based on driving simulations with few on-site experiments and lacking quantitative analysis of night driving safety impact.

Darko Babi´c et al.[2] (2022) investigated road marking reflectivity's effect on LSS detection quality and field of view, determining a minimum reflectivity value greater than 88 $mcd\cdot m^{-2}\cdot lx^{-1}$. Babić D and Cajner H[3] (2020) designed driving simulation experiments to analyze road marking's effect on young drivers' night driving speed. Zhao Luhua and Xu Xiaoqian et al. (2023) designed a simulation experiment to study the

G. Chen et al. (eds.), *Proceedings of the 2024 International Conference on Rail Transit and Transportation (ICRTT 2024)*, Advances in Engineering Research 254,
https://doi.org/10.2991/978-94-6463-610-9_35

effect of marking luminance on driving behavior. Through field driving experiments on highways with different retroreflective coefficients, we analyze driver's eye movement and speed at night and establish a driving behavior matrix to quantify the effects on night driving safety.

2 DATA SOURCES AND RESEARCH METHODS

2.1 Driving Behavior Matrix

Driving Behavior Matrix Composition. Driving behavior matrix is a comprehensive record of the dynamic changes of vehicle driving data in a specific scene, which can reflect driving behavior characteristics. Based on the driving behavior matrix in the experimental scenario, three driving behaviors(Speed Stability, Distraction of attention and Front gaze stability) were defined.

The coefficient of variation reflects data dispersion. In this paper, speed stability M_1 is defined by speed coefficient of variation. The speed stability characteristic parameter measures vehicle state with frequent acceleration/deceleration and high-speed fluctuation. As shown in formula (1), larger $M_1(t)$ at time t indicates more unstable speed:

$$M_1(t) = \frac{std\left(V(t-2),\cdots,V(t)\right)}{mean\left(V(t-2),\cdots,V(t)\right)} \tag{1}$$

In formula (1), std(•) is standard deviation; V(t) is target vehicle speed at time t.

Distraction of attention M_2 is defined as the proportion of mean $g_{mean}(t)$ of sweeps number of interest areas on both sides in the total number of sweeps g(t) within time t. Larger M_2 indicates more distracted attention:

$$M_2(t) = \frac{g_{mean}(t)}{g(t)} \tag{2}$$

Fixation time is the total time the subject's sight stays in an area. Longer fixation means more attention. Front gaze stability M_3 is defined as the proportion of mean $D_{mean}(t)$ of fixation time of frontal interest area in overall saccade within fixed time t. (Shown in formula (3)):

$$M_3(t) = \frac{D_{mean}(t)}{D(t)} \tag{3}$$

Using 5 seconds as the sequence length, the MOR method was used to calculate characteristic parameters. The MOR method analyzes and estimates driving behavior safety on different marked roads to avoid subjective risk estimation[5]. The safety metric calculation method maps the driving behavior matrix into a time series of n (n = 3) driving behavior characteristic parameters, forming the driver's bad driving behavior matrix B. (Shown in formula (4)):

$$B = \begin{pmatrix} M_1 & M_2 & M_3 \end{pmatrix} \tag{4}$$

Acquiring characteristic parameters in driving process requires thresholds to determine safe state. When ith characteristic parameter value is higher than threshold M_i^*, it indicates a safe driving hazard. Conversely, it indicates no hazard and safe driving. This paper uses the quartile difference method to determine driving safety thresholds. The formula (5) for calculating safety threshold M for each characteristic parameter is:

$$M = Q_{up} + 1.5I \tag{5}$$

Eigenvalues of Driving Behavior Matrix. The eigenvalue of a driving behavior matrix represents the comprehensive safety degree. Lower eigenvalue means safer driving behavior. Otherwise, the less secure it is.

By calculating the proportion of vehicle $M_i(t)$ exceeding the threshold through formula (6), the instantaneous score S_i (t) of i_{th} driving behavior of the vehicle at time t can be obtained, and the higher the score, the lower the safety degree. When M_i (t) does not exceed the threshold, the score is 0, which means that the driving is safe in the time t. S_i (t) represents the score of i_{th} driving behavior exceeding the safety threshold:

$$S_i(t) = f(x) = \begin{cases} \dfrac{M_i(t) - M_i^*}{M_i^*} & , M_i(t) > M_i^* \\ 0 & , M_i(t) \le M_i^* \end{cases} \tag{6}$$

S_i (t) is cumulatively averaged over time, and the average time score A_i of i_{th} bad driving behavior of each vehicle is obtained in formula (7):

$$A_i = \frac{1}{T}\sum_{i=0}^{T} S_i(t) \tag{7}$$

Where: T is the observation duration.

Normalize A_i to obtain A_{Ni} and perform weighted averaging to obtain the comprehensive driving score λ of the route, that is, the eigenvalue λ of the route driving behavior matrix:

$$\lambda = \sum_{i=1}^{n} \omega_i A_{Ni} \tag{8}$$

Where: ω_i is the weight of i_{th} driving behavior, representing its proportion in all driving behaviors, and the sum of weights of all bad driving behaviors is 1.

After calculating the driver's comprehensive dangerous driving score λ according to formula (8), the weight value of each dangerous driving behavior needs to be calculated. The CRITIC weight method is used to avoid subjective factor bias. In the calculation, multiply comparison intensity by conflict index to get information C_i and normalize to get the final weight[6].

The information C_i of i_{th} type of bad driving behavior is calculated as follows:

$$C_i = s_i R_i = s_i \sum_{j=1}^{n} \left(1 - r_{ij}\right) \quad (9)$$

In formula (9), s_i is the contrast intensity of ith driving behavior characteristic parameter. R_i is the conflicting index. r_{ij} is the correlation coefficient between i_{th} parameter and bad driving behavior parameter. After normalizing C_i, final weight ω_i is obtained as formula (10)：

$$\omega_i = \frac{C_i}{\sum_{i=1}^{n} C_i} \quad (10)$$

2.2 Field Driving Experiment

The experimental sections were selected from three straight highways (Weiqing Expressway, Jingtai Expressway, and Jinan Bypass Expressway). There were no street lamps on both sides and only vehicle high beams were used. The total number of experimenters was 15 (12 males and 3 females). The experiment was conducted at night.

The instrument used to measure the retroreflective coefficient of the markings was the Jingqu RP-R18 marking retroreflectometer, and the data were collected using the Tobii pro glasses 2 eye-tracker. Fig 1 shows the Tobii pro glasses 2 eye-tracker.

Fig. 1. Tobii pro glasses 2 eye-tracker

The drivers wore calibrated eye-tracking devices and conducted the driving experiment. At the end, Tobii pro lab software was used for preliminary data processing. Combined with the heat map of the driver's gaze point, the experimenter's gaze direction was divided into three interest zones (front, left marking line, and right marking line) by mechanical division of the field of view plane. As shown in Fig. 2.

Fig. 2. Focus Point Heat Map and Zone of Interest Segmentation

The data obtained from the experiment were divided into two parts: velocity data collected by the velocimetry equipment, and eye movement index data extracted by Tobii pro lab software from the recorded video of the eye-tracking experiment. Some of the speed and eye movement index data are shown in Tables 1 through 3.

Table 1. Speed data

Vehicle number	1	1	1	1	1	1	1	1	…
Time(s)	5	10	15	20	25	30	35	40	…
Speed(km/h)	44	45	58	70	79	89	99	108	…

Table 2. Gaze duration data

Media	a1-Weiqing	a2-Jingtai	a3-Jinan Bypass	b1-Weiqing	b2-Jingtai	b3-Jinan Bypass	…
The right side of the marking	0	0	7096	0	1019	80	…
Front side of the marking	84588	89646	29163	98901	102160	93844	…
The left side of the marking	0	0	939	6316	1959	160	…

Table 3. Sweep frequency data

Media	a1-Weiqing	a2-Jingtai	a3-Jinan Bypass	b1-Weiqing	b2-Jingtai	b3-Jinan Bypass	…
Number of right sweeps	0	0	27	0	3	1	…
Number of front sweeps	150	13	40	8	20	23	…
Number of left sweeps	0	0	3	1	4	1	…

3 DATA ANALYSIS

3.1 ANOVA Variance Test

To test the effect of the level of marker retro-reflectivity on the characteristic parameters of the driving behavior matrix, a one-way ANOVA was performed using SPSS software. The ANOVA results for speed, number of marker sweeps, and forward gaze time are shown in Table 4-6:

Table 4. ANOVA results for the average speed of the experimenters

Source	Sum of Squares	Degrees of Freedom	Mean Square	Fe	Significance P
Between groups	4343.458	2	2171.729	61.962	.000
Within groups	1472.077	42	35.049		
Total	5815.534	44			

Table 5. ANOVA for the number of marking line sweeps

Source	Sum of Squares	Degrees of Freedom	Mean Square	Fe	Significance P
Between groups	3848.225	2	1924.113	38.211	.000
Within groups	7150.464	142	50.355		
Total	10998.690	144			

Table 6. ANOVA for forward gaze time

Source	Sum of Squares	Degrees of Freedom	Mean Square	Fe	Significance P
Between groups	56368.454	2	28184.227	36.090	.000
Within groups	114799.721	147	780.950		
Total	171168.174	149			

The results show that the level of retro-reflectivity of the markings has a significant effect on the driver's speed, the number of sweeps, and the forward gaze time during nighttime driving.

3.2 Driving Behavior Matrix Analysis

Safety Thresholds for Driving Behavior Matrix Feature Parameters. The analysis of driving behavior matrix characteristic parameters' distribution can better reflect driving behavior characteristics and determine the abnormal behavior boundary. According to the distribution, the quartile difference method is used to calculate the threshold value of the characteristic parameters. The calculation results are shown in Table 7:

Table 7. Threshold values of characteristic parameters of driving behavior matrix

Experimental road	Speed Stability	Distraction of attention	Front gaze stability
Weiqing 800mcd·m^{-2}·lx^{-1}	0.068	0.111	0.981
Jingtai 500mcd·m^{-2}·lx^{-1}	0.054	0.246	0.984
Jinan Bypass 70mcd·m^{-2}·lx^{-1}	0.079	0.505	0.941

Driving Behavior Matrix Eigenvalues. Based on the CRITIC assignment method, the contrast intensity s_i, conflict indicator R_i, and the amount of information C_i of each driving behavior characteristic parameter were calculated. The final weights ω_i were obtained as 0.351, 0.369, and 0.280 respectively. The results are shown in Table 8:

Table 8. Results of the CRITIC weighting method

	Speed Stability	Distraction of attention	Front gaze stability
Contrast intensity (s_i)	0.235	0.323	0.256
Conflict indicator (R_i)	1.896	1.449	1.386
Amount of information (C_i)	0.445	0.469	0.355
Final weights (ω_i)	0.351	0.369	0.280

The three driving behavior scores are weighted and averaged to obtain the eigenvalue of the driving behavior matrix with different marking retroreflection coefficients.

The measured data of Weiqing and Jingtai Expressway are in the safe driving behavior interval. Their driving behavior matrix eigenvalue is infinitely close to 0, indicating an acceptable impact of their marking retroreflection level on traffic safety. The driving behavior matrix eigenvalue of Jinan Bypass Expressway is as in formula (11):

$$\lambda = \sum_{i=1}^{n} \omega_i A_{Ni} = 0 * 0.351 + 0.15 * 0.369 + 0.15 * 0.280 = 0.09735 \quad (11)$$

The Jinan Bypass Expressway with a retroreflection coefficient of 70 $mcd{\cdot}m^{-2}{\cdot}lx^{-1}$ is less safe for nighttime driving than the Weiqing and Jingtai Expressway, with higher safety risk. Thus, it needs highway marking maintenance to improve road safety.

4 CONCLUSIONS

In this paper, field driving experiments were conducted on three highways with different marker retroreflectivity levels. Eye movement indicators and speed data of night-driving drivers were collected using eye-tracking and speed measuring equipment. Through Tobii Pro lab, SPSS software, and the driving behavior matrix method, the safety effects of different retroreflective coefficients on night driving were analyzed. It was found that a significant increase in retroreflective coefficient greatly improves night driving safety. By calculating the eigenvalues of the driving behavior matrix, it was found that drivers on the Weiqing and Jingtai expressways are relatively safe at night. However, on the Jinan Bypass Expressway, the eigenvalue is 0.09735, indicating that the marking line retroreflectivity affects safe driving to some extent and has low safety stability.

This paper only investigated three road marking retroreflectivity coefficients on drivers' safety at night, and this limitation is that the markings are inconsistent.In the future, more highways will be selected to study the impact of retroreflectivity on night driving safety.

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