Effectiveness of Active Luminous Lane Markings on Highway at Night: A Driving Simulation Study

Bencheng Zhu 1, Cancan Song 1,*, Zhongyin Guo 1, Yu Zhang 2 and Zichu Zhou 1

1 The Key Laboratory of Road and Traffic Engineering of Ministry of Education, Tongji University, Shanghai 201804, China; bencheng@tongji.edu.cn (B.Z.); zhongyin@tongji.edu.cn (Z.G.); 1410705@tongji.edu.cn (Z.Z.)
2 Shandong Road Region Safety and Emergency Support Laboratory, Shandong Transportation Institute, Jinan 250102, China; zhangyu@sdjtky.cn
* Correspondence: songcancan@tongji.edu.cn; Tel.: +86-021-6958-5723

Abstract: Road lane markings play an essential role in maintaining traffic order and improving traffic safety and efficiency. Active luminous lane markings have emerged with advances in technology recently. However, it is still not completely clear what impact their application will have on drivers. This paper aimed to study the effectiveness of active luminous lane markings on highways at night. A driving simulation experiment was carried out based on advanced driving simulators at Tongji University. The driving simulation experiment involved 31 participants and 9 simulation scenes with 6 different types of lane markings models and the same 2-way highway segment, which was 5300-m long with four 3.75-m wide driving lanes. The study participants drove through the simulated highway while the vehicle operation data and the driver’s eyes changing data were continuously captured. Overall, the pupil area change rate, steering wheel speed, brake pedal force, gas pedal, lane departure, and operating speed indicators were selected to evaluate the effectiveness of the active luminous lane markings. The results are shown as follows: (1) the active luminous lane markings have excellent visual recognition performance at night. Compared with the passive luminous lane markings, the active luminous markings can reduce the mental and physical loads of drivers, increase the early braking distance significantly, improve the lane-keeping ability and smooth the operating speed; (2) for the specific parameter settings of the active luminous lane markings at night, the yellow lane markings are better than the white ones, the point-line-type lane markings are superior to the conventional-type ones, and the blinking frequency is reasonable to set, at a moderate level, as 40 times per min. The results suggest that there are positive effects of active luminous lane markings on the promotion of highway traffic safety and efficiency at night, providing theoretical support for the popularization and application of active luminous road lane markings.

Keywords: highway; traffic safety and efficiency; lane markings; active luminous; effectiveness evaluation; driving simulation

1. Introduction

Since the appearance of road lane marking, it has played an essential role in maintaining traffic order and improving traffic safety and efficiency [1,2]. However, the research [3] has pointed out the effectiveness of road lane markings depends on their visibility. If road lane markings cannot be seen and recognized by drivers, their function cannot be fully explored.

The primary way to enhance the visibility of lane markings is to increase their brightness [4–6]. According to different light-emitting modes of lane markings, they can be divided into two types: passive luminous and active luminous. As Smadi [7] pointed out, the light-emitting principle of passive luminous lane markings is to reflect other light sources, such as car lights, street lights, and sunlight. This type of lane markings has been widely used because of their retroreflective properties and low cost, approximately...
accounting for more than 99% of the total road lane markings [8,9]. However, this type of lane markings has many shortcomings. Firstly, as concluded by Hautière [10], the visibility of passive luminous lane markings significantly reduces under adverse environmental conditions, such as night, rain, and smog, which greatly increases the traffic accident risk. Furthermore, the main material that makes passive luminous lane marking reflect light is glass beads embedded in it. However, in most cases, the glass beads will be worn away quickly, resulting in a shorter service life of the lane markings [11].

As for active luminous systems, Costa and Lantieri [12,13] confirmed that an integrated lighting-warning system for pedestrian crossings was effective in increasing motorists’ yielding to pedestrians during nighttime and proved that flashing in-curb light-emitting diode (LED) strips and flashing orange beacons were very effective in increasing the night-time safety of pedestrian crossings. Active luminous lane markings also include two types: the light-storage type and the LED type. As for light-storage-type lane markings, the main component is a long afterglow material, which works in a mode of “absorbing light, storing light and emitting light” [14–16]. Light-storage lane markings have been applied in rural road traffic safety signs [17], tunnel emergency escape systems [18], and urban slow-track decoration [19] for trial. However, the brightness and color temperature of light-storage lane markings cannot always vary with the external environment. Studies and applications of those markings have also shown that the light-emitting time is not long enough. Thus, light-storage lane markings have not yet been applied on a large scale. The LED-type active luminous lane marking is a new type of marking developed with LED technology and solar technology [20]. Wu [21] and Zhang [22] each invented an LED tidal lane marking, controlling the tidal traffic flow by changing the color of built-in LED lights. Wang [23] invented LED traffic marking lines for guiding the queue of vehicles at the intersection, which are mainly composed of a base embedded with LED lamp beads and a transparent body covered thereon. Zhao [24] investigated the safety of an LED traffic marking in a freeway tunnel by a driving simulator experiment, indicating that the markings could reduce driver anxiety, boredom caused by the dark and monotonous tunnel driving environment. Lin [25] found that LED markings are effective in mitigating wrong-way entries onto limited-access facilities.

As Babic et al. [26] pointed out, during daytime, the visibility of road markings is based on the color contrast between the marking and the roadway and is generally not an issue since there is sufficient light. On the other hand, during nighttime, there is less amount of light available to drivers, increasing driving risk on highways. Therefore, based on the modern concept of “self-explaining roads”, which aims to convey the upcoming road situation to drivers in an easy and intuitive way [27,28], there is a strong demand for the use of active luminous markings to actively provide drivers with road information at night. In the upcoming decades, active luminous lane markings would replace the existing passive luminous lane markings wholly or partially. However, the LED-type lane marking is a relatively new field of research and has not been widely used on highways so far. Meanwhile, the application of active luminous lane markings still lacks theoretical basis, such as the marking setting parameters of type, color, and blinking frequency. It is worth studying what impact the application of active luminous lane markings will have on drivers and evaluating its effectiveness. As for the evaluation methods in the research of Ghasemi et al. [29], the driver’s visual behavior and vehicle operation data can be collected to evaluate its effectiveness.

Therefore, to study the effectiveness of active luminous lane markings on highways at night, a driving simulation experiment was carried out in this paper. Six different types of lane markings and nine different driving simulation scenes were constructed in this experiment. The pupil area change rate, steering wheel speed, brake pedal force, gas pedal, lane departure, and operating speed were used as the indicators of the response characteristics of drivers to different lane markings. The conclusions of this study have great theoretical significance in terms of the application of active luminous lane markings.
2. Methods

2.1. Scenes Design

The high-fidelity driving simulator at Tongji University was used for the experiment. With the same road alignment, the nine scenes in Table 1 were built using SCANeRstudio1.6 software. The 2-way highway segment was 5300 m long with four 3.75-m wide driving lanes, consisting of several straight segments, four curved segments with different radii, and two tunnel segments. The detailed design parameters of the road alignment are shown in Table 2. Six different lane markings in the driving simulation scenes are presented in Table 3. According to the National Standards of China [1], the conventional-type lane marking lines had a pattern of a 6-m stripe and a 9-m gap, and the point-line-type lane marking lines had a pattern of a 0.15-m stripe and a 15-m gap. The widths of both types of lane markings line were 0.15 m.

| Scenes | Parameters of Lane Markings |
|--------|----------------------------|
|        | Shape of Lane Markings | Color | Whether it is Active Luminous or Not | Whether it is Blinking or Not | Blinking Frequency (times/min) |
| Scene 1 | conventional type | white | no | no | - |
| Scene 2 | conventional type | yellow | no | no | - |
| Scene 3 | conventional type | white | yes | no | - |
| Scene 4 | conventional type | yellow | yes | no | - |
| Scene 5 | point-line type | white | yes | no | - |
| Scene 6 | point-line type | yellow | yes | no | - |
| Scene 7 | point-line type | yellow | yes | yes | 20 |
| Scene 8 | point-line type | yellow | yes | yes | 40 |
| Scene 9 | point-line type | yellow | yes | yes | 60 |

In order to eliminate the significant difference between the artificial luminance level in the simulator and the actual luminance level in the real-world condition, the visual recognition distances of the lane marking samples were tested on an actual road before the driving simulation experiment. Taking the visual recognition distance as the control index, the brightness, size, and inclination of lane markings in the driving simulation scenes were adjusted to achieve the same visual recognition distance as reality.
Table 3. Different lane markings in the driving simulation scenes.

| Type | With the Vehicle Beams on | With the Vehicle Beams off |
|------|---------------------------|----------------------------|
| 1    | Conventional type, white, passive luminous |
| 2    | Conventional type, yellow, passive luminous |
| 3    | Conventional type, white, active luminous |
| 4    | Conventional type, yellow, active luminous |
In order to further improve the test reliability, finally, 279 sets of valid test data were available.

### Table 3. Cont.

| Type | With the Vehicle Beams on | With the Vehicle Beams off |
|------|---------------------------|----------------------------|
| 5    | Point-line type, white, active luminous | ![Image](image1) |
| 6    | Point-line type, yellow, active luminous | ![Image](image2) |

#### 2.2. Participants

The experiment was a repeated measures design. According to the sample size calculation method [30,31], 31 participants (17 males and 14 females) were recruited as the drivers. The age of participants ranged from 22 to 51 years (mean = 37.5; SD = 10.2). All participants held a valid driver’s license for more than 3 years. Besides, all of them were physically and mentally healthy with normal eye vision.

#### 2.3. Experimental Procedure

Before the formal experiment, the drivers were required to conduct a 10-min preliminary experiment to get familiar with the driving simulator. Then, they completed the nine simulation scenes in turn. To ensure the drivers not to be affected by intrinsic factors (memory function, fatigue, etc.), they were required to have a rest between two successive scenes. Furthermore, each driver completed the driving simulator experiment in random order. The order in which each driver completed scenes 1–9 was random and different. In this way, as far as the whole experiment was concerned, the resulting errors could be offset. During the experiment, the drivers were required to drive in the right lane all the way with the vehicle beams on, using the vehicle high and low beams as their needed. The SCAnNeRStudio1.6 software can record the drivers’ control parameters (steering wheel, brake pedal, gas pedal, etc.) and the vehicle running parameters. The drivers’ eyes change parameters were collected through the Dikablis head-mounted eye tracker. Finally, 279 sets of valid test data were available.

#### 2.4. Data Analysis

All statistical analyses were conducted using SPSS Statistics software [32]. For the data-fitting normal distribution, the analysis of variance (ANOVA) was used for the hypothesis
test. This study evaluated the effectiveness of active luminous lane markings from three aspects, i.e., the driver’s mental load, physical load, and vehicle running state. Furthermore, six indicators are selected (i.e., pupil area change rate, steering wheel speed, brake pedal force, gas pedal, lane departure, and operating speed).

In the study of Zhang et al. [33], the pupil area change rate was selected as the indicator of the driver’s mental load. A greater pupil area change rate was found to be associated with a higher mental load. The mathematical equation for calculating the pupil area change rate is shown as follows:

\[ R_i = \frac{|A_{i+1} - A_i|}{A_i}, \]  

where \( R_i \) represents the change rate of point \( i \), \( A_{i+1} \) represents the pupil area of \( i + 1 \) point, and \( A_i \) represents the pupil area of point \( i \).

In this experiment, the drivers mainly needed to control the steering wheel, brake pedal, and gas pedal, which represented the drivers’ physical loads.

Besides, the positions where the drivers started to brake can be derived from the brake pedal force indicator. When they started to brake, it means that they were aware of the dangerous road ahead. The starting point of each curve and tunnel segments were predefined in the simulation scenes. In this way, the distance between the starting position of braking and the starting point of each curve and tunnel segments can be calculated. Longer distance means that the drivers recognized the adverse road segment ahead earlier. That is to say, the visual recognition performance of lane markings was better.

The lane departure referred to the distance from the center line of the right lane in this paper. Reflecting the driving stability, it can also be used to judge the consistency of the driver’s trajectory and the road alignment. A smaller lane departure means a better road alignment induction effect of lane markings.

The operating speed value can also represent the reflected performance of the lane markings. In terms of the whole driving process, a higher and smoother operating speed means that the lane markings had a better performance for improving traffic efficiency and stability.

3. Results and Discussion

The mean values, SDs, F statistics, and significance levels of the six selected indicators in the nine scenes were calculated and tested, as shown in Table 4.

| Indicators               | Mean (SD)          | F     | P     |
|-------------------------|--------------------|-------|-------|
|                         | Scene 1 | Scene 2 | Scene 3 | Scene 4 | Scene 5 | Scene 6 | Scene 7 | Scene 8 | Scene 9 |       |       |
| Pupil area change rate (%) | 1.61   | 1.46   | 1.35   | 1.28   | 1.28   | 1.26   | 1.29   | 1.14   | 1.24   | 5.11 | 2.24 × 10^{-6} ** |
| (2.82)                  | (2.45)  | (1.64) | (1.64) | (1.59) | (2.38) | (1.47) | (1.35) | (1.67) |       |     |       |
| Steering wheel speed (°/s) | 0.81   | 0.81   | 0.79   | 0.77   | 0.75   | 0.75   | 0.83   | 0.74   | 0.73   | 0.82 | 0.58 |
| (1.36)                  | (1.28)  | (1.35) | (1.26) | (1.26) | (1.24) | (1.39) | (1.16) | (1.20) |       |     |       |
| Brake pedal force (N)   | 1.95    | 1.64   | 1.47   | 1.81   | 1.33   | 1.14   | 1.32   | 1.42   | 1.56   | 6.86 | 4.95 × 10^{-9} ** |
| (4.34)                  | (3.49)  | (2.94) | (3.15) | (2.91) | (2.20) | (2.48) | (3.28) | (3.16) |       |     |       |
| Gas pedal (%)           | 14.25   | 15.16  | 14.69  | 16.60  | 15.08  | 15.91  | 15.07  | 16.12  | 16.73  | 13.92 | 0 **  |
| (6.39)                  | (7.77)  | (6.53) | (7.24) | (7.41) | (7.15) | (6.45) | (7.41) | (8.86) |       |     |       |
| Lane departure (m)      | 0.09    | 0.04   | 0.08   | 0.04   | 0.05   | 0.02   | 0.05   | 0.07   | 0.01   | 37.67 | 0 **  |
| (0.25)                  | (0.26)  | (0.25) | (0.25) | (0.25) | (0.26) | (0.23) | (0.23) | (0.21) |       |     |       |
| Operating speed (km/h)  | 88.51   | 91.11  | 91.52  | 91.83  | 89.52  | 89.74  | 93.44  | 93.41  | 93.42  | 19.99 | 0 **  |
| (13.38)                 | (13.22) | (12.24)| (12.72)| (12.75)| (13.20)| (14.10)| (13.57)| (14.71)|       |     |       |

\( F \) value from the ANOVA test statistic. ** Significant at the 0.01 level.

3.1. Pupil Area Change Rate.

The results of pupil area change rate are shown in Figure 1.
Gas pedal (%) 14.25 (6.39) 15.16 (7.77) 14.69 (6.53) 16.60 (7.24) 15.08 (7.41) 15.91 (7.15) 15.07 (6.45) 16.12 (7.41) 16.73 (8.86) 13.92 0 **

Lane departure (m) 0.09 (0.25) 0.04 (0.26) 0.08 (0.25) 0.04 (0.25) 0.05 (0.25) 0.02 (0.26) 0.005 (0.23) 0.00007 (0.23) 0.01 (0.21) 37.67 0 **

Operating speed (km/h) 88.51 (13.38) 91.11 (13.22) 91.52 (13.24) 91.83 (12.72) 89.52 (12.75) 89.74 (13.20) 93.44 (14.10) 93.41 (13.57) 93.42 (14.71) 19.99 0 **

3.1. Pupil Area Change Rate.

The results of pupil area change rate are shown in Figure 1.

As shown in Table 4, the pupil area change rates in the nine scenes were significantly different at the 0.01 level. Compared with those in scenes 1 and 2, the change rates of the average pupil areas in scenes 3–9 were smaller. The results showed that the drivers’ mental loads in the active luminous lane marking scenes were lower than those in passive luminous lane marking scenes. The average pupil area change rate in scene 2 was smaller than that in scene 1. The average pupil area change rate in scene 4 was smaller than that in scene 3, and the average pupil area change rate in scene 6 was smaller than that in scene 5. The results showed that the yellow lane markings were more conducive to reducing the driver’s mental load than the white lane markings at night. The average pupil area change rate in scene 5 was smaller than that in scene 3, and the average pupil area change rate in scene 6 was smaller than that in scene 4, which indicated that the point-line-type active luminous lane markings were more effective in reducing the driver’s mental load than the conventional-type ones. As for the blinking frequency, the average pupil area change rate in scene 7 was greater than that in scene 6, the average pupil area change rates in scenes 8 and 9 were smaller than in scene 6, and the average pupil area change rate in scene 8 was the smallest, which indicated that a moderate blinking frequency (40 times per min) showed more positive effects on the reduction of the drivers’ mental load at night.

3.2. Driver’s Physical Load

As shown in Table 4, at the 0.01 level, the population means of the brake pedal force and gas pedal in the nine scenes were significantly different, while those of the steering wheel speeds in the nine scenes were not significantly different. In order to integrate these three indicators, the Min–Max method was used to normalize them calculated by the following equation:

\[ x' = \frac{x - x_{\text{min}}}{x_{\text{max}} - x_{\text{min}}}, \]

where \( x' \) represents the normalized value, and \( x_{\text{min}} \) and \( x_{\text{max}} \) represent the minimum and maximum values of this indicator, respectively.
According to Equation (2), the steering wheel speed, brake pedal force, and gas pedal were normalized, and the results are shown in Table 5. It was found that when the drivers judged that the road ahead was dangerous or they were in a panic state, they operated the steering wheel faster or step on the brake pedal more forcefully. On the contrary, when the drivers judged that the road ahead was safe, they controlled the steering wheel smoothly and press the gas pedal to get a faster speed. In this experiment, the design of road alignment was gentle. Therefore, a faster steering wheel speed and a greater brake pedal force implied a greater difference between the driver’s cognition of the road alignment ahead and the road design itself, that is to say, the lane markings had a worse alignment guidance effect. The lane markings had a better linear guidance effect with a larger gas pedal and a smaller difference between the driver’s cognition of the road ahead and the road design itself. Therefore, when calculating the driver’s physical load, the steering wheel speed and brake pedal force indicators were negative, while the gas pedal was positive, shown as follows:

\[ L_p = -N_s - N_b + N_g, \]  

where \( L_p \) represents the driver’s physical load, \( N_s \) represents the normalized value of the steering wheel speed, \( N_b \) represents the normalized value of the brake pedal force, and \( N_g \) represents the normalized value of the gas pedal. The calculated results are shown in Table 5, and a larger value means a better effect of lane markings.

**Table 5.** Normalized values of the steering wheel speed, brake pedal force, and gas pedal.

| Scene | Scene | Scene | Scene | Scene | Scene | Scene | Scene | Scene | Scene |
|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| \( N_s \) | 0.80  | 0.80  | 0.60  | 0.40  | 0.20  | 0.20  | 1.00  | 0.10  | 0.00  |
| \( N_b \) | 1.00  | 0.62  | 0.41  | 0.83  | 0.23  | 0.00  | 0.22  | 0.35  | 0.52  |
| \( N_g \) | 0.00  | 0.37  | 0.18  | 0.95  | 0.33  | 0.67  | 0.33  | 0.75  | 1.00  |
| \( L_p \) | -1.80 | -1.05 | -0.83 | -0.28 | -0.10 | 0.47  | -0.89 | 0.31  | 0.48  |

According to the same comparison method as the pupil area change rate in Section 3.1, we can draw the following conclusions. Overall, the driver’s physical loads in the active luminous lane marking scenes were lower than those in the passive luminous lane marking scenes. This result is consistent with the research conclusion of Horberry et al. [34], which found that the workload was rated as lower for the enhanced markings. As for the color and type, the yellow lane markings were more effective in reducing the driver’s physical load than the white ones at night. The point-line-type active luminous lane markings were more conducive to reducing the driver’s physical load than the conventional-type ones at night. Different from the conclusion drawn by the pupil change rate, in terms of the driver’s physical load, a higher blinking frequency (60 times per min) showed more positive effects on the reduction of the driver’s physical load at night.

### 3.3. Brake Distance

We found that the drivers decelerated before entering the curve and tunnel segments. As analyzed in Section 2.4, the visual recognition distance of the lane markings can be obtained from the brake pedal force. The distances between the point where the drivers started to brake and the starting point of next segment were calculated in Table 6. A larger visual recognition distance means that the drivers braked earlier.
Table 6. Distances between the point where the drivers started braking and the starting point of next road segment (m).

| Scheme 1 | D1 (R1) | D2 (R2) | D3 (R3) | D4 (R4) | D5 (T1) | D6 (T2) | Average | SD |
|----------|---------|---------|---------|---------|---------|---------|---------|----|
| Scene 1  | 50      | 30      | 15      | 5       | 80      | 35      | 36      | 23 |
| Scene 2  | 40      | 25      | 15      | 10      | 145     | 30      | 44      | 43 |
| Scene 3  | 75      | 45      | 35      | 30      | 305     | 95      | 98      | 88 |
| Scene 4  | 90      | 50      | 40      | 40      | 290     | 90      | 100     | 81 |
| Scene 5  | 115     | 55      | 60      | 50      | 350     | 125     | 126     | 97 |
| Scene 6  | 135     | 75      | 45      | 55      | 375     | 120     | 134     | 104|
| Scene 7  | 120     | 70      | 35      | 50      | 325     | 45      | 108     | 94 |
| Scene 8  | 170     | 90      | 55      | 50      | 425     | 50      | 140     | 124|
| Scene 9  | 175     | 85      | 75      | 35      | 375     | 75      | 137     | 106|

For the average visual recognition distance of the lane markings in Table 6, similar to the study of Bella et al. [35], we found that the visual recognition distances of the active luminous lane markings were greater than those of the passive luminous lane markings. For the color and type of the active luminous lane markings at night, yellow was better than white, and the point-line type was better than the conventional type. Consistent with the conclusion drawn by the pupil change rate, from the perspective of the visual recognition distance, a moderate blinking frequency (40 times per min) was more effective for improving the visual recognition distance at night.

3.4. Lane Departure

The lane departures of the nine simulation scenes are shown in Figure 2, with the values greater than zero means biased to the left and those less than zero means biased to the right.

As shown in Table 4, the lane departures of the nine scenes were significantly different at the 0.01 level. By comparing lane departures of the nine scenes, similar conclusions can be found with the pupil change area rate. Furthermore, the areas of the shaded portion
in Figure 2 were calculated to evaluate the lane departure quantitatively. Three areas, i.e., areas above and below the zero line and the total area, were calculated separately, as shown in Table 7.

**Table 7.** The areas of the lane departures in different simulation scenes (m²).

| Scenes | Area above the Zero Line | Area below the Zero Line | Total Area |
|--------|--------------------------|--------------------------|------------|
| Scene 1 | 860                      | 395                      | 1255       |
| Scene 2 | 690                      | 485                      | 1175       |
| Scene 3 | 785                      | 375                      | 1160       |
| Scene 4 | 660                      | 435                      | 1095       |
| Scene 5 | 470                      | 610                      | 1080       |
| Scene 6 | 365                      | 655                      | 1020       |
| Scene 7 | 505                      | 480                      | 985        |
| Scene 8 | 460                      | 405                      | 865        |
| Scene 9 | 475                      | 470                      | 945        |

From either the means or the total areas of the lane departures in the nine simulation scenes, the same conclusions can be obtained. The lane departures in the active luminous lane marking scenes were greatly reduced compared to those in the passive luminous lane marking scenes. The yellow lane markings showed more positive effects on the reduction of the lane departure than the white ones at night. The point-line-type active luminous lane markings reduced the lane departures than the conventional-type ones at night. Consistent with the conclusion drawn by the pupil change rate, in terms of the lane departure, a moderate blinking frequency (40 times per min) was more effective in reducing the lane departure at night. Chang et al. [36] found the effectiveness of passive luminous longitudinal edgeline pavement markings. Liu et al. [37] confirmed the conventional passive luminous markings satisfy spatial lane length requirements by increasing the lane-keeping ability. Based on the above analysis, it was found that the lane marking in scene 8 was the best in this paper. The lane-keeping ability in scene 8 was improved by 31% compared with that in scene 1.

3.5. Operating Speed

The operating speeds of the nine simulation scenes are shown in Figure 3.

On the whole, the operating speeds in the active luminous lane markings scenes were smoother than those in the passive luminous lane markings scenes. Meanwhile, it was found that the active luminous lane markings increased the driving speed by comparing the means of the operating speed. The smoother and higher operating speeds are possibly associated with the lower mental and physical loads in the active luminous lane marking scenes, leading to faster but more controlled driving. This result is consistent with the study of Ranney and Gawron [38]. Therefore, it can be concluded that the active luminous and yellow lane markings are more effective to increase driver confidence and improve running efficiency than the passive luminous and white lane markings at night. However, for the type and blinking frequency, the conclusions are different from the pupil area change rate. Since the means of the operating speeds in scenes 5 and 6 were smaller than those in scenes 3 and 4, we cannot accurately conclude that point-line-type active luminous lane markings are better than conventional-type ones at night. From the perspective of the operating speed, a low blinking frequency (20 times per min) showed more positive effects on the improvement of running efficiency at night.
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Figure 3. Operating speeds in different simulation scenes.

3.6. The Overall Comprehensive Effectiveness Evaluation

The above content evaluated the effectiveness of the active luminous lane markings from the perspective of a single indicator. In this section, a comprehensive evaluation method on the effectiveness of the active luminous lane markings is given. According to Equation (2), the six indicators in Table 4 were normalized, and the results are shown in Table 8.

Table 8. Normalized values of the six selected indicators in the nine scenes.

| Scene | $N_p$ | $N_s$ | $N_b$ | $N_g$ | $N_l$ | $N_o$ | $E_{lm}$ |
|-------|-------|-------|-------|-------|-------|-------|---------|
| 1     | 1.00  | 0.80  | 1.00  | 0.00  | 1.00  | 0.00  | −3.80   |
| 2     | 0.68  | 0.80  | 0.62  | 0.37  | 0.44  | 0.53  | −1.65   |
| 3     | 0.45  | 0.60  | 0.41  | 0.18  | 0.89  | 0.61  | −1.56   |
| 4     | 0.30  | 0.40  | 0.83  | 0.95  | 0.44  | 0.67  | −0.35   |
| 5     | 0.30  | 0.20  | 0.23  | 0.33  | 0.44  | 0.20  | −0.75   |
| 6     | 0.26  | 0.20  | 0.00  | 0.67  | 0.22  | 0.25  | 0.24    |
| 7     | 0.32  | 1.00  | 0.22  | 0.33  | 0.22  | 1.00  | −0.27   |
| 8     | 0.00  | 0.10  | 0.35  | 0.75  | 0.05  | 0.99  | 1.30    |
| 9     | 0.21  | 0.00  | 0.52  | 1.00  | 0.11  | 1.00  | 1.15    |

The above six indicators completely included the driver’s mental, physical, and vehicle running status. The effectiveness of the lane markings can be evaluated through an integrated indicator $E_{lm}$, a newly proposed indicator that evaluated the effectiveness of the lane markings in this paper. As analyzed in Section 2.4, for the two indicators—gas pedal and operating speed, a larger value means a better effect of the lane marking, so these two indicators were set as positive values. For the other four indicators, a smaller value means a better effect of the lane markings, so these four indicators were set as negative values. The calculation equation of $E_{lm}$ was written as follows:

$$E_{lm} = -N_p - N_s - N_b + N_g - N_l + N_o,$$  

(4)
where $E_{lm}$ represents the comprehensive effectiveness of the lane markings, $N_p$ represents the normalized value of the pupil area change rate, $N_s$ represents the normalized value of the steering wheel speed, $N_b$ represents the normalized value of the brake pedal force, $N_g$ represents the normalized value of the gas pedal, $N_l$ represents the normalized value of the lane departure, and $N_o$ represents the normalized value of the operating speed. The calculation results of $E_{lm}$ are shown in Table 8.

Based on the $E_{lm}$ of the nine lane markings scenes, some conclusions can be drawn. Compared with those in scenes 1 and 2, the $E_{lm}$ in scenes 3–9 were greater. It was shown that the active luminous lane markings were comprehensively effective compared with the passive luminous lane markings at night. In terms of the color, the $E_{lm}$ in scene 4 was greater than that in scene 3, and the $E_{lm}$ in scene 6 was greater than that in scene 5. It was shown that the yellow active luminous lane markings were more effective than the white active luminous lane markings at night. For the types, the $E_{lm}$ in scene 5 was greater than that in scene 3, and the $E_{lm}$ in scene 6 was greater than that in scene 4, which indicated that the point-line-type active luminous lane markings were more effective than the conventional-type active luminous lane markings at night. As for the blinking frequency, the $E_{lm}$ in scene 7 was less than that in scene 6, the $E_{lm}$ in scenes 8 and 9 were greater than that in scene 6, and the $E_{lm}$ in scene 8 was the maximum, which showed that a moderate blinking frequency (40 times per min) was more effective at night. The comprehensive effectiveness of the active luminous lane markings is beneficial to promote traffic safety on highways at night.

3.7. Application Prospect Analysis

Active luminous lane markings have excellent visual recognition performance at night. They can be used in high-risk road segments caused by poor road alignment conditions such as small radii, long longitudinal slopes, bridges, tunnels, and complicated meteorological conditions such as rain, fog, and ice. Furthermore, active luminous lane markings could be improved. Not only can they emit light actively, they can also have some informational and digital functions. At the same time, a rescue management platform could be built based on intelligent active luminous lane markings. The platform can control and reduce secondary accidents caused by the sudden release of meteorological and unexpected events.

The point-line-type active luminous pavement markings are buried in the asphalt concrete pavement. In practical use, there are three power supply modes: one is to build a solar-power-generation panel on the surface of a block to generate electricity by using solar energy; the second mode is to embed wires under a block to supply power to all blocks through wired transmission; the final mode is to build a radio receiving module inside a block and use a mobile vehicle with a wireless charging module to charge blocks on the road regularly. None of these three methods will significantly increase the cost of infrastructure construction.

Intelligent active luminous lane markings have the following potential advantages. Firstly, intelligent active luminous lane markings can be used for forwarding road alignment guiding and vehicle wake display. According to the real-time detection of meteorological conditions, vehicle type, vehicle speed, events, and other traffic parameters, the traffic risk can be divided into different levels, and the corresponding traffic control strategy is developed. The color of markings can be changed in real-time, such as green for normal traffic, yellow for warning, and red for prohibition. It can not only improve the visual distance but also deliver information, which is helpful to promote traffic safety. Besides, by setting a certain blinking frequency and switching different color schemes of lane markings, it will also produce good results for preventing fatigue driving. Compared with the use of directional rumble strips proposed by Xue et al. [39] to promote driving safety, the intelligent active luminous lane markings proposed in this paper will not cause vibrations to vehicles, thereby making drivers and passengers more comfortable.

Secondly, many other kinds of innovations could be carried out in active luminous lane markings. For example, light-transmitting concrete could be introduced into highways.
Then, intelligent active luminous lane markings can be composed of light-transmitting concrete and LED [40]. This kind of lane markings is embedded in the pavement. Besides, intelligent active luminous lane markings are tightly integrated with new pavement structures such as piezoelectric pavement and solar photovoltaic pavement [41]. They adopt an integrated power supply mode of piezoelectric and solar energy. This is a fusion practice of green highway, safe highway, and smart highway concept.

Thirdly, the identification of lane markings in all weather conditions is a technical problem restricting autonomous vehicles. Similar to the idea of Mao et al. [42] that applies markings in the dynamic reversible lane of an intelligent cooperative vehicle infrastructure system, based on the intelligent active luminous lane markings imagined in this paper, electronic communication components could be embedded to improve the digitization and intelligence levels of the lane markings. In this way, vehicle-to-road coordination can be realized. This provides a new solution for the identification of lane markings in complex weather conditions for autonomous vehicles.

4. Conclusions

This paper studied the effectiveness of active luminous lane markings on highways at night based on driving simulators. The main conclusions are summarized as follows:

- The active luminous lane markings had a better visual recognition performance at night, which was improved by about two times compared to the passive luminous lane markings.
- Compared with the passive luminous lane markings, the active luminous lane markings can reduce the mental and physical loads of drivers, increase the early braking distance by approximately two times, improve the lane-keeping ability by approximately 31%, smoothing the operating speed and be more conducive to improving traffic efficiency and stability. These improvements have great potential for enhancing road safety in night conditions.
- For the specific parameter settings of the active luminous lane markings on highways at night, the yellow lane markings were better than the white ones, the point-line-type lane markings were superior to those of the conventional-type ones, and the blinking frequency was reasonable to set, at a moderate level, as 40 times per min.

These findings have theoretical significance for the popularization and application of active luminous road lane markings. Even so, we still have some work to do in the future. Next, we will further study the control strategy of intelligent active luminous lane markings. Different control methods should be studied according to different levels of traffic risk.

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