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Research Article

Effectiveness and Optimal Location of Real-Time Traffic Conflict Risk Warning System for Rural Unsignalized Intersections: A Driving Simulation Study

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The real-time traffic conflict risk warning system (RTCRWS) is proposed as a new proactive crash prevention and control strategy for intersections designed to reduce traffic on the main road to rural unsignalized intersections when a vehicle enters the access roads. This study aims at evaluating the effectiveness of the RTCRWS with different locations based on a driving simulation experiment. In this study, four types of the RTCRWS installation location schemes (i.e., no installation, 50 m/100 m/150 m away from the unsignalized intersection) are designed. Twenty-two experienced drivers participated in the driving simulation experiment, and seven evaluating indicators representing driving behavior data are proposed. Two methods to analyze the data are applied: (1) descriptive analysis of driving behavior characteristics different location schemes of the RTCRWS and (2) entropy weight-fuzzy comprehensive evaluation of the RTCRWS. The results show that the RTCRWS has a significant effect on slowing vehicles when approaching the rural unsignalized intersections. If the location of the RTCRWS is 50 m, 100 m, and 150 m from the intersection, the comprehensive score of fuzzy evaluation is 75.82, 74.91, and 77.22, respectively, which implies that the scheme with the RTCRWS 150 m ahead of the intersection is the most effective.

1. Introduction

In recent years, with the increasing number of vehicles and drivers in China, the traffic environment is becoming more dangerous and complex, resulting in many traffic safety problems (e.g., diversification of vehicles, the sharp increase in traffic demand, and the integration of poor driving behavior). According to the National Bureau of Statistics data [1], the number of road traffic crashes in China has remained high in the past five years; road traffic crashes have become an important factor that hinders the economic development of China and threatens the safety of people's lives and property. As a key part of the road traffic network, local problems (congestion, crashes, etc.) that occur at intersections can be rapidly propagated and accumulated with a nonlinear model. It often causes a large-scale, long-term damage or even complete paralysis of the function of the road network and traffic system in a short time, seriously reducing the service level of the road network [2].

Meanwhile, the increasingly complex traffic environment on China's rural roads has created traffic safety problems including complex roads, diverse vehicles, surging traffic demand, and irregular driving behavior, in particular the crash rate at unsignalized intersections in rural areas has increased year by year, and traditional traffic safety facilities such as warning lights and deceleration pavement markings have been unable to meet the requirements of the proactive crash prevention. According to statistics, from 2017 to 2019, half of traffic crashes in China occurred in rural areas, and 23% of rural traffic crashes occurred at intersections; among them, failure to yield to traffic, violation of traffic signals, and illegal overtaking are the main causes of intersection crashes [3]. Therefore, how to improve the comprehensive safety level of unsignalized intersections has become a key issue in the field worldwide.

New proactive prevention and control technology for intersections such as real-time traffic conflict risk warning system (RTCRWS) at rural unsignalized intersections has been implemented in Yunnan Province, China. The RTCRWS's physical model consists of solar charging panel, light-emitting diode (LED) display screen, post, and integrated chassis (e.g., controller, communication module, sensor, and battery pack). During operation, RTCRWS detects the traffic conditions at intersections in real time and effectively delivers traffic conflict risk warning information and dynamic road condition information to drivers using graphic digital light multimode LED boards, to realize the proactive prevention and control of traffic crash risk and safety improvement from the source, as shown in Figure 1.

In this paper, the following relevant hypotheses are developed for the effectiveness of the RTCRWS: (1) The RTCRWS can help influence the driving behavior of drivers by providing real-time warning information; (2) according to the installation location, the effect of RTCRWS is also different; and (3) a networked vehicle test platform is built based on a driving simulator. This platform can help to verify the effectiveness of RTCRWS.

The remainder of this paper is organized as follows: Firstly, the related research is summarized, and then the driving simulation experiment platform, experimental design, and data collection are discussed. Finally, the experimental results, discussions, conclusions, and future research direction are given.

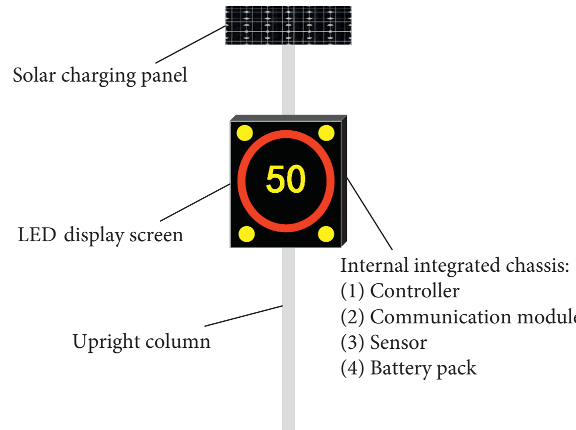


Figure 1: Physical model of RTCRWS.

2. Literature Review

The current research objects for traffic sign effectiveness evaluation are mostly static traffic signs, and the research contents are mostly focused on speed limit management, visual recognition of signs, and driver's driving load. Moreover, with the deepening of related research, the effectiveness evaluation of traffic safety facilities at intersections has gradually changed from the traditional qualitative evaluation to the quantitative evaluation, which is based on driving behavior and driver's psychophysiological characteristics.

(1) Speed limit management: The reasonable layout of traffic safety facilities can effectively reduce the occurrence of traffic crashes [4, 5]. Dario Bellin et al. [6] investigated the relationship between alignment, maintenance conditions, and speed limit signs, and the results of the study indicated that excessive use of speed limit signs may lead to unsafe driving habits and traffic violations. Further studies have shown that speed limit signs with warning signs are more effective and valid than simple speed limit signs [7].

(2) Driving load evaluation: Electroencephalography (EEG) signals were used to study the effects of Adaptive Cruise Control (ACC) on driving load and risk perception mechanisms [8]. Gianluca Di Flumeri et al. [9] tested an algorithm for evaluating the mental load of drivers under real traffic conditions; however, because the sample size of the experiment is too small, the reliability of the algorithm needs to be further verified.

(3) Visibility of traffic signs: Eye-movement tracks are often used to study drivers' perception of traffic signs. Dario Babić et al. [10] studied their understanding of traffic sign images and found that the characteristics of gestures on traffic signs have a significant impact on eye-movement behavior. Van Houten et al. [11] found that the accurate recognition and compliance of drivers to the intersection stop sign were improved after adding the LED display to the intersection stop sign.

However, literature has shown that the research on the effectiveness of static traffic signs is still at the traditional passive, postevaluation level, lacking in initiative, predictability, and safety, and cannot meet the needs of active prevention and early warning of traffic crashes. Based on this, active safety prevention and control technology at intersections has become a research hotspot, and variable message signs (VMS) as its typical product have attracted much attention. As an important equipment for information release in the intelligent transportation systems, VMS has been widely used in road management, providing drivers with real-time traffic conditions, and issuing early warning information, which is of significant value in guiding drivers to drive safely and reduce traffic crashes [12]. Choi et al. [13] used importance-performance analysis (IPA) model to study the importance and satisfaction of observers to the information provided by VMS and studied the measures to improve the quality of traffic information service. At present, most of the research on active safety prevention and control technology at unsignalized intersections focused on field testing of the effectiveness of dynamic risk warning signs, and the methods are mainly based on vehicle collision risk assessment and vehicle speed distribution. Swedish Road Administration (SRA) developed a variable speed limit system for intersections and tested the system from 2003 to 2007, the results show that the average speed of vehicles passing through intersections is reduced by 14 km/h under the action of the variable speed limit system at intersections, and the acceptable interspersing gap for vehicles has been increased by 1 to 2 seconds [14]. The Rural Intersection Active Warning System (RIAWS) [15] was proposed by New Zealand Transport Agency (NZTA) to reduce the number of traffic crashes and improve safety at high-risk intersections, and it was verified through experiments that RIAWS could effectively reduce the speed of vehicles [16].

There are few quantitative studies on driver behavior characteristics, and no intrinsic link between driver behavior characteristics and dynamic risk warning signs and optimal locations of unsignalized intersections has been established. Given this, the objective of this paper is to evaluate the effectiveness of RTCRWS at rural unsignalized intersections with different locations. According to the conclusions, the authors would like to put forward theoretical suggestions on the effectiveness and evaluation method of RTCRWS at rural unsignalized intersections in China, to rationalize the location of rural unsignalized intersection traffic safety facilities to reduce the occurrence of traffic crashes.

3. Data Preparation

3.1. Participants. A total of thirty-eight experienced drivers (age 22–55, $M = 41.35$, SD = 8.91; 23 males and 15 females) were recruited from Kunming, Yunnan Province, China. The original data of the subjects' driving behavior were screened and preprocessed, and the seriously defective data were eliminated, and twenty-two groups ($M = 38.81$, SD = 9.57; 13 males and 9 females) of effective data were obtained. The participants have had a valid driver's license over 3 years; the uncorrected visual acuity is more than 4.8 and the corrected visual acuity is 4.9 and above; there is no mental or major illness affecting driving performance.

3.2. Equipment. This research was conducted in the KMRTDS driving simulator, which is based on the Road Traffic Simulation Laboratory of the Faculty of Transportation at Kunming University of Science and Technology. Liu et al. [17] verified the speed effectiveness of the KMRTDS driving simulator under different plane pairs. Chen et al. [18] calibrated the three-dimensional virtual image object space size of the KMRTDS driving simulator according to the principle of the similar triangle and verified the experimental effectiveness of the KMRTDS driving simulator based on the fuzzy neural network method [19]. KMRTDS driving simulator was used in the experiment, through which real-time data were collected, including vehicle operation parameters (i.e., speed, acceleration, accelerator brake pedal depth, lateral offset, and steering wheel angle), which were recorded at the frequency of 60 Hz. The virtual schemes were projected onto a three-channel embracing screen, providing a 140° horizontal visual field and a 40° vertical visual field as shown in Figure 2(a). ErgoLAB psychological instrument was used to collect ECG and EDA data of experimental drivers, which adopts wireless radio frequency physiological recording technology and collects data without interference from natural factors through data recorders and sensors, as shown in Figure 2(b).

3.3. Scenarios. The VS-Design 3D scene design software independently developed by the Road Traffic Simulation Laboratory of Kunming University of Science and Technology was used to build four virtual simulation schemes of RTCRWS.

(1) Warning strategy of RTCRWS : The warning strategy of RTCRWS is divided into two types (a vehicle is approaching from the lateral direction, and no vehicle is approaching from the lateral direction), the pattern flashing frequency is 1.00 Hz, and the warning content switching frequency is 0.33 Hz, as shown in Table 1.

(2) Scheme 1: as a control group, no RTCRWS is installed at the intersection. When the test vehicle enters the unsignalized intersection from south to north, it conflicts with lateral traffic, as shown in Figure 3(a).

(3) Scheme 2 to 4: RTCRWS is installed at 50 m, 100 m, and 150 m ahead of the intersection in the driving direction of the test vehicle. When the test vehicle enters the unsignalized intersection, it reminds the driver that there is a vehicle approaching from the lateral direction and needs to slow down. Then, the conflicting vehicle conflicts with the test vehicle, as shown in Figure 3(b) to 3(d).

3.4. Driving Behavior Characteristic Index. The entropy weight-fuzzy comprehensive evaluation is employed in three aspects: psychophysiological characteristics, driving safety characteristics, and operating behavior characteristics of drivers, which are described as follows:

(1) Psychophysiological indexes: heart rate growth rate and the growth rate of electrodermal activity (EDA).

(2) Driving safety indexes: coefficient of speed variation, jerk standard deviation (Jerk SD).

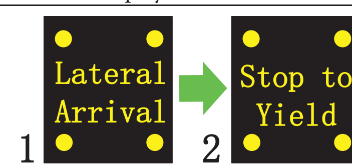
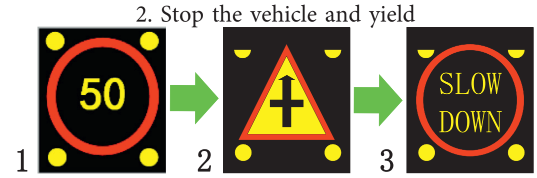
(3) Operating behavior indexes: angle entropy of steering wheel, maximum depression of the brake pedal, and braking cycles.

3.5. Procedure. The total time of the experiment is about 1 h, divided into four stages. In stage 1, subjects are required to fill out a driver information form to record their basic information (including name, gender, age, and driving experience) and receive training to familiarize themselves with

(a) (b)

Figure 2: Experimental equipment. (a)KMRTDS driving simulator. (b)ErgoLAB psychological instrument.

Table 1: Warning strategy of RTCRWS.

Situation	Display information
A vehicle is approaching from the lateral direction	 1. A vehicle is approaching from the lateral direction 2. Stop the vehicle and yield
No vehicle is approaching from the lateral direction	 1. Traffic sign with a speed limit 50 km/h 2. Intersection ahead 3. Reduce speed and slow down

the KMRTDS interface before the start of the experiment. In stage 2, subjects are allowed to participate in a preexperiment of about 5–8 minutes. The main purpose of the pre-experiment is to familiarize subjects with and master the driving simulator, to ensure that each subject could operate the driving simulator proficiently during the formal experiment. In stage 3, twenty-two screened subjects will take a formal test; the staff helped subjects wear ErgoLAB psychological instruments. The subjects were asked to keep their head as stable as possible and abide by their own driving habits. While driving, the subjects encountered scheme 1 to scheme 4 in turn. In case of emergency, measures should be taken to ensure vehicle safety, including speed change and parking braking. In the process of driving, subjects are required not to drive into the opposite lane. In stage 4, experimental data were collected. Driving safety indexes and operating behavior indexes were recorded by KMRTDS. The ErgoLAB psychological instruments were used to record heart rate growth rate and EDA.

4. Methodology

The entropy-fuzzy comprehensive evaluation model is used to evaluate the effectiveness and optimal location of RTCRWS. The fuzzy comprehensive evaluation method uses the principle of fuzzy synthesis and membership degree to describe fuzzy boundaries and comprehensively evaluates the membership grade of things to be evaluated from multiple indexes. It has the advantages of fuzziness, weight processing, hierarchy, and cyclability, can organically combine qualitative and quantitative factors, and makes the objective of the conclusion accurate and credible. The framework of this paper is shown in Figure 4.

4.1. Relevance Analysis of Driving Behavior Characteristic Index. Pearson correlation analysis [20] is carried out on the driver behavior characteristic indicators under different positions from scheme 1 to scheme 4, as shown in Table 2.

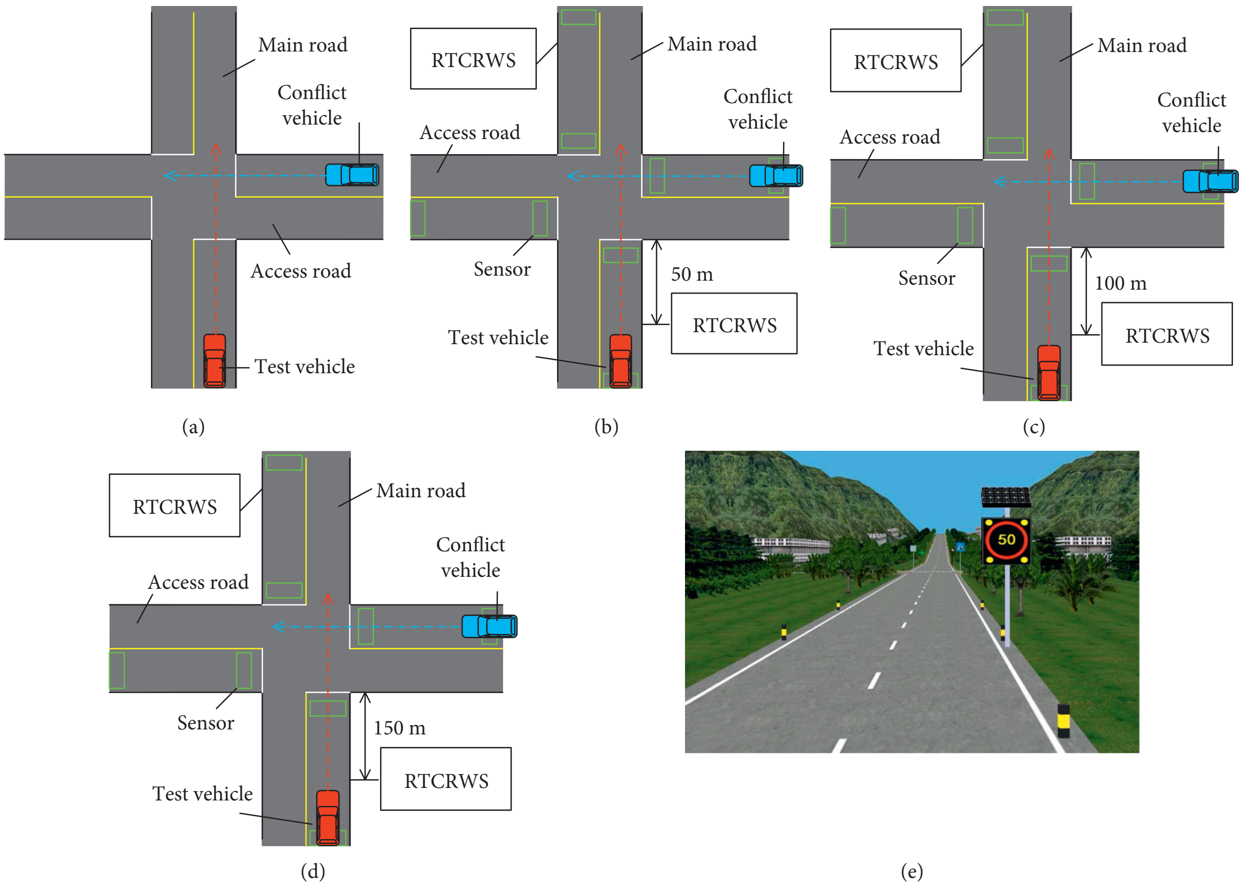


Figure 3: Schemes location of RTCRWS. (a)Scheme 1. (b)Scheme 2. (c)Scheme 3 (d)Scheme 4. (e)Schematic diagram of RTCRWS experimental location.

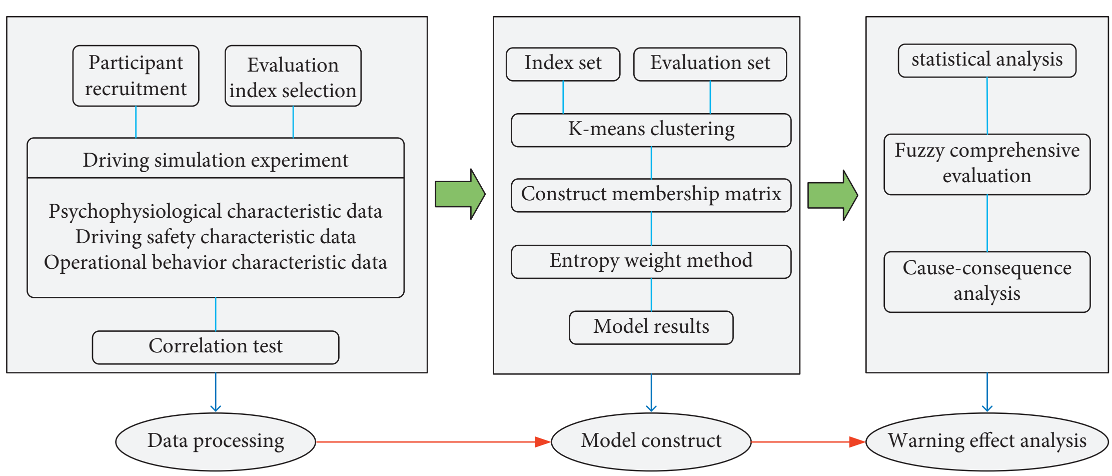


Figure 4: Study framework layout.

It is shown from Table 1 that the driver's coefficient of speed variation and heart rate growth rate indexes are positively correlated with the location of RTCRWS; i.e., the indicator values gradually increase with the increase of RTCRWS deployment distance, while the Jerk SD, steering wheel angle entropy, maximum depression of the brake pedal, and braking cycles are all negatively correlated with the location of RTCRWS, and the correlation is significant.

Table 2: Correlation analysis data.

Evaluation index	Locations	
	Pearson correlation	P-value (two-tailed)
Coefficient of speed variation	0.732*	0.035
Jerk SD	−0.551**	-0.009
Heart rate growth rate	0.734*	0.025
The growth rate of EDA	−0.004	0.980
Angle entropy of steering wheel	−0.811*	0.037
Maximum depression of the brake pedal	−0.308*	0.039
Braking cycles	−0.540*	0.049

**Significant at 0.01 level (two-tailed).* Significant at 0.05 level (two-tailed).

There is a negative correlation between the growth rate of EDA and the location of RTCRWS, but the correlation is not significant. Therefore, six indicators significantly related to the distance of RTCRWS deployment were selected to construct the index set (coefficient of speed variation, Jerk SD, heart rate growth rate, angle entropy of steering wheel, maximum depression of the brake pedal, and braking cycles).

4.2. Constructing Index Set and Evaluation Set. The corresponding evaluation index system is determined according to the evaluation object, and the evaluation factor set was established. In this paper, six evaluation indexes, including coefficient of variation of vehicle speed, Jerk SD, angle entropy of steering wheel, maximum depression of the brake pedal, braking cycles, and heart rate growth rate indexes, are selected to construct the evaluation factor set. The evaluation factor set is $U = \{u_1, u_2, u_3, u_4, u_5, u_6\}$. And the evaluation is divided into four levels: excellent, good, medium, and poor; then the evaluation set is $V = \{v_1, v_2, v_3, v_4\}$.

4.3. Determining the Evaluation Matrix. K-means clustering algorithm is employed in clustering the evaluation factors to determine the value range of each grade in the evaluation set V, as shown in equations (1) to (2) [21]:

$$d_{\text{is}}(p_i, s_i) = \sqrt{(p_{i1} - s_{i1})^2 + (p_{i2} - s_{i2})^2 + \cdots + (p_{\text{in}} - s_{\text{in}})^2}, \quad (1)$$

$$s_k = \frac{\sum_{i=1}^{N} p}{N}, \quad (2)$$

where $d_{\text{is}}(p_i, s_i)$ is Euclidean distance, p_{in} is the n-th attribute of the n-th object, s_{in} is the n-th attribute of the n-th cluster center, s_i is the initial clustering center, p_i is the element of the data sample matrix T_i, s_k is the k-th clustering center, and N is the object data for the k-th cluster center.

4.4. Membership Matrix. In the process of fuzzy evaluation, the accuracy of the calculation of membership degree of evaluation index is related to the credibility of the evaluation results, and the selection of appropriate membership function is an important part of the evaluation process. The membership function expression used in this paper is as follows [22].

Assuming that the present value of the evaluation index is λ_i, and the allowable range of its value is $[a_{\text{pi}}, b_{\text{pi}}]$, and $[a_{\text{ij}}, b_{\text{ij}}]$ is the value range of each evaluation grade. The membership degree r_{ij} of the index $u_i = (i = 1, 2, \ldots, m)$ to the evaluation grade $v_j = (j = 1, 2, \ldots, n)$ is analyzed, and the membership degree matrix R is constructed, as shown in equations (3) to (6).

$$R = \begin{bmatrix} r_{11} & r_{12} & \cdots & r_{1n} \\ r_{21} & r_{22} & \cdots & r_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ r_{m1} & r_{m2} & \cdots & r_{\text{nn}} \end{bmatrix}, \quad (3)$$

$$r_{\text{ij}} = \begin{cases} \dfrac{-\rho_1}{\left|b_{\text{ij}} - a_{\text{ij}}\right|}, & \lambda_i \in \left[a_{\text{ij}}, b_{\text{ij}}\right], \\ \dfrac{v}{(\rho_2 - \rho_1)}, & \lambda_i \notin \left[a_{\text{ij}}, b_{\text{ij}}\right] \& \rho_1 \neq \rho_2, \\ -\rho_1 - 1, & \lambda_i \notin \left[a_{\text{ij}}, b_{\text{ij}}\right] \& \rho_1 = \rho_2, \end{cases} \quad (4)$$

$$\rho_1 = \left|\lambda_i - \frac{1}{2}\left(b_{\text{ij}} + a_{\text{ij}}\right)\right| - \frac{1}{2}\left(b_{\text{ij}} - a_{\text{ij}}\right), \quad (5)$$

$$\rho_2 = \left|\lambda_i - \frac{1}{2}\left(b_{\text{pi}} + a_{\text{pi}}\right)\right| - \frac{1}{2}\left(b_{\text{pi}} - a_{\text{pi}}\right). \quad (6)$$

4.5. Determining Index Weight by Entropy Method. According to the basic principle of the entropy weight method, each evaluation index is studied, and the information entropy value e_i and its weight w_j of each evaluation index are calculated, as shown in (7) and (8).

$$e_j = -\frac{1}{\ln s} \sum_{i=1}^{s} z_{\text{ij}} \ln z_{\text{ij}}, \quad (7)$$

$$w_j = \frac{1 - e_j}{\sum_{i=1}^{m} \left(1 - e_j\right)}, \quad (8)$$

where z_{ij} is the characteristic proportion of the i evaluation object under the j index; if $z_{\text{ij}} = 0$, then define $\lim_{z_{\text{ij}} \longrightarrow 0} \ln z_{\text{ij}} = 0$.

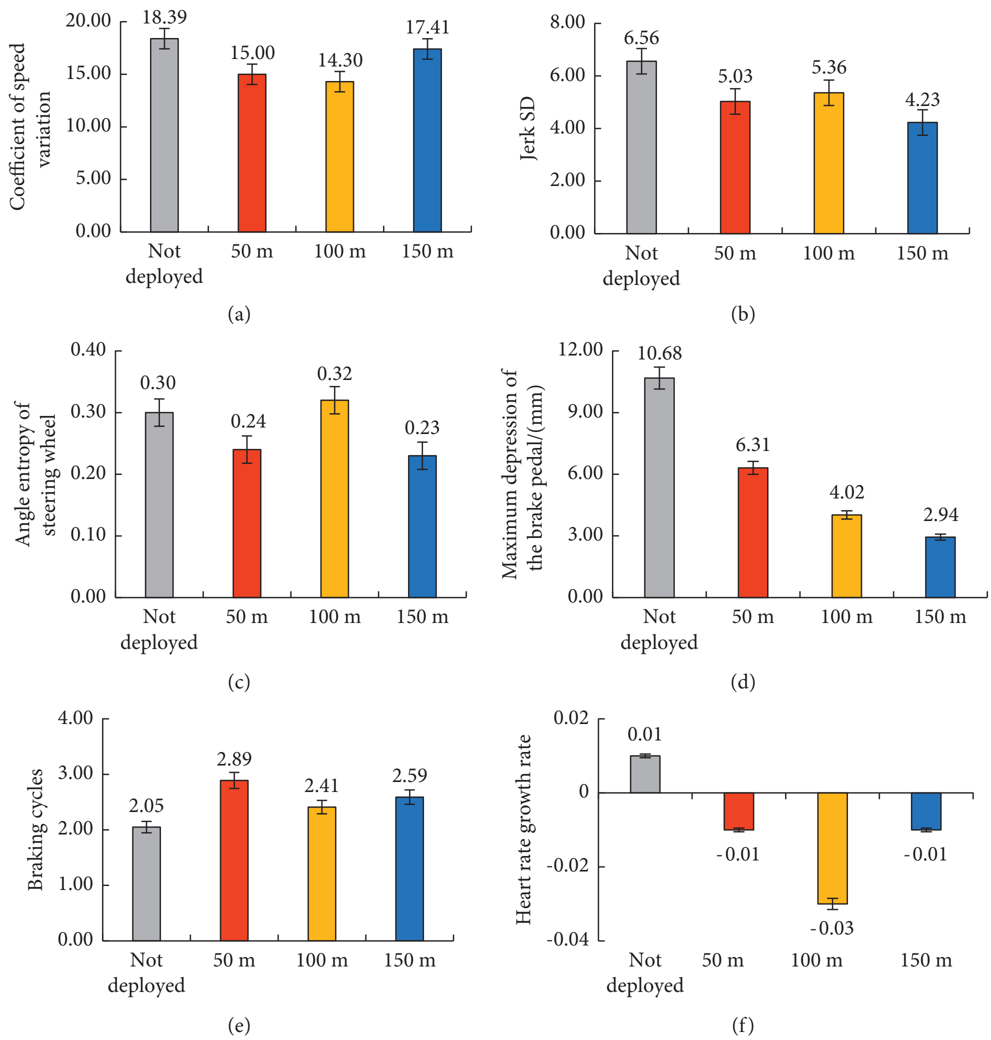


FIGURE 5: The indexes of three schemes. (a) Coefficient of speed variation. (b) Jerk SD. (c) Angle entropy of steering wheel. (d) Maximum depression of the brake pedal. (e) Braking cycles. (f) Heart rate growth rate.

4.6. Fuzzy Comprehensive Evaluation. After normalization, the membership fuzzy relation matrix R' was obtained. The fuzzy comprehensive calculation is carried out by using the weight vector $W = (w_1, w_2, \ldots, w_m)$ of the index and the membership fuzzy relation matrix R', and the warning effect evaluation vector B of the risk early warning system is obtained, as shown in (9).

$$B = W \circ R' = (b_1, b_2, \ldots, b_n), \tag{9}$$

where $'' \circ ''$ is the fuzzy operator; take the weighted average type, that is, $b_j = \sum_{i=1}^{m} (w_i \cdot r'_{ij})$.

5. Results

5.1. Impact of Real-Time Risk Warning Locations on Driving Behavior Characteristics. Statistics of driver's coefficient of speed variation, Jerk SD, HRGR, angle entropy of steering wheel, maximum depression of the brake pedal, and braking cycles in the three schemes were collected, as shown in Figure 5.

The variation range of the driver's speed is characterized by the coefficient of speed variation index. The coefficient of the speed variation index is used to measure the difference of the variation range of vehicle speed, which is positively correlated with the possibility of the crash [23]. Jerk SD represents the stability of vehicle driving state and has a negative correlation with vehicle driving safety [24]. As shown in Figure 5(a) and 5(b), the coefficient of speed variation index and Jerk SD index of the subjects with RTCRWS scheme is lower than that of the scheme without RTCRWS, indicating that RTCRWS can effectively control the driver's speed variation and improve the traffic safety at unsignalized intersections. Moreover, the coefficient of speed variation index value of laying RTCRWS at 50 m is the best (value = 14.30), which is lower than other schemes. The Jerk SD index with RTCRWS scheme installed at 100 m from the intersection is better and lower than other schemes (value = 4.23).

The steering wheel angle entropy is selected to evaluate the steering wheel handling stability of the driver, and the entropy value increases gradually with the enhancement of operation disorder [25, 26]. As shown in Figure 5(c), the steering wheel angle entropy index of installing RTCRWS at 150 m from the intersection is better and lower than the other two RTCRWS schemes (value = 0.23). However, the index value of scheme 3 is higher than that of the control group, which means that the installation of RTCRWS at 100 m will have a bad effect on the steering wheel handling and stability of the driver. Maximum depression of the brake pedal indicates the driver's perception of sensitivity to conflict and has a negative correlation with the driver's perception of risk conflict. The braking cycles reflect the warning effect of RTCRWS on drivers and have a positive correlation with drivers' awareness of active speed control [27]. It can be seen in Figure 5(c) and 5(d) that the steering wheel angle entropy index and maximum depression of the brake pedal index in scheme 4 were the best and smallest (value = 0.23, 2.94). It shows that the installation of RTCRWS at 150 m from the intersection can improve the steering wheel operation stability and conflict perception ability of the driver and reduce the driver's workload. In Figure 5(e), the driver in scheme 2 has the least braking number index (value = 2.89) and the strongest awareness of active speed control. This shows that the installation of RTCRWS at 50 m from the intersection is helpful to improve the driver's awareness of active speed control.

Heart rate growth rate is used to characterize the psychological changes and stress degree of drivers. From Figure 5(f), it can be seen that the heart rate growth rate index of the driver under the three schemes is negative, the heart rate growth rate index of installing RTCRWS at 100 m from the intersection is the lowest (value = -0.03), indicating that the arrangement of RTCRWS can effectively alleviate the psychological tension of the driver passing through the unsignalized intersection, and the index value of the driver in scheme 3 is the lowest, indicating that RTCRWS is installed 100 m ahead of the intersection, and the driver's state is the most relaxed.

5.2. Entropy-Fuzzy Comprehensive Evaluation. The K-mean clustering algorithm was used to cluster six evaluation indicators, including coefficient of variation of vehicle speed, Jerk SD, angle entropy of steering wheel, maximum depression of the brake pedal, braking cycles, and heart rate growth rate indexes. The range of values for each rank in the evaluation set V is shown in Table 3. After the calculation of membership degree (equation (3) to (6)), a membership degree matrix $(m \times n)$ with m evaluation indexes and n evaluation grades is formed, as shown in Table 4. The weight of each evaluation index is calculated according to the basic principle of the entropy weight method, as shown in Table 5 ((7) and (8)).

Using fuzzy synthesis (9), the evaluation results of the three layout schemes of RTCRWS are shown in Table 6. However, according to the principle of maximum membership degree, the warning effect grades of the three schemes are all "excellent," which indicates that the installation location of RTCRWS plays a certain role in improving the level of traffic safety at intersections. To compare the advantages and disadvantages of various RTCRWS deployment schemes in detail, the fractional gradient matrix $G = (90, 80, 70, 60)^T$ and the comprehensive score F of the warning effect of schemes are defined as shown in (10). The fuzzy synthetic evaluation results and the comprehensive score of the warning effect of the three deployment schemes are shown in Figure 6.

$$F = B \cdot G, \tag{10}$$

where B is the warning effect evaluation vector of RTCRWS.

As shown in Figure 6, although the warning effect grades of the three schemes are all "excellent," the comprehensive score of scheme 4 is the best. Therefore, according to the six evaluation indexes of driving behavior characteristics, it is best to set up a risk early warning system at 150 m ahead of the intersection.

6. Discussions

The objective of this paper was to evaluate the effectiveness of RTCRWS at rural unsignalized intersections considering different installation locations using entropy weight-fuzzy comprehensive evaluation. The driving simulation experiment was conducted to collect the objective data of driving behavioral characteristics of the subjects.

We found that the location of RTCRWS is significantly related to the coefficient of variation of vehicle speed, heart rate growth rate, Jerk SD, steering wheel angle entropy, maximum depression of the brake pedal, and braking cycles in Table 1. Although the three schemes of RTCRWS at unsignalized rural intersections (50 m, 100 m, and 150 m) have significant warning effects as shown in Table 5, different schemes have different warning effects on drivers; for example, scheme 2 can effectively enhance drivers' awareness of taking braking measures to control speed (Figure 5(e)). Scheme 3 can alleviate the psychological tension of drivers and reduce the possibility of crashes (Figures 5(a) and 5(f)). Scheme 4 can make the driving state of the vehicle more stable, reduce the driver's workload, and improve their sensitivity to conflict perception (Figures 5(b)–5(d)). Among them, the warning effect of RTCRWS at 150 m ahead of the intersection is the most significant as shown in Figure 6.

Huang et al. [28] studied the driver's recognition of LED proactive luminous traffic signs and concluded that the recognition distance of LED active luminous traffic signs at night is 1.3 to 1.9 times longer than that of static traffic signs. Compared with static traffic signs, RTCRWS has the advantages of automatic luminous, proactive warning, and strong night recognition. RTCRWS can cooperate to perceive the traffic situation within the intersection, intelligently study and judge the potential traffic crash risk, issue early warning information to drivers in real time, improve drivers' safety and comfort, and meet the requirements of proactive crash prevention at intersections. The reasonable arrangement of RTCRWS can further improve the comprehensive safety service level of rural highway traffic security facilities and promote the development of rural unsignalized

Table 3: Range of evaluation indexes.

Evaluation index	Current situation	Level 1	Level 2	Level 3	Level 4
Coefficient of speed variation	18.39	(3.09, 7.19)	(7.20, 12.43)	(12.44, 26.74)	(26.75, 41.62)
Jerk SD	6.56	(0.16, 1.02)	(1.03, 4.01)	(4.02, 10.69)	(10.70, 14.64)
Angle entropy of steering wheel	0.30	(0.00, 0.09)	(0.10, 0.21)	(0.22, 0.38)	(0.39, 0.47)
Maximum depression of the brake pedal	10.68	(0.00, 4.00)	(4.01, 9.28)	(9.29, 13.18)	(13.19, 20.00)
Braking cycles	2.05	(0.00, 1.00)	(1.01, 3.00)	(3.01, 4.00)	(4.01, 8.00)
Heart rate growth rate	-0.02	(-0.14, -0.10)	(-0.09, -0.01)	(0.00, 0.06)	(0.07, 0.11)

Table 4: Membership matrix.

Evaluation index	Level 1	Level 2	Level 3	Level 4
Coefficient of speed variation	-0.404	-0.265	0.416	-0.336
Jerk SD	-0.464	-0.285	0.381	-0.393
Angle entropy of steering wheel	-0.778	-0.600	0.500	-0.600
Maximum depression of the brake pedal	-0.418	-0.131	0.357	-0.212
Braking cycles	-0.339	0.477	-0.319	-0.489
Heart rate growth rate	-0.381	0.125	-0.133	-0.409

Table 5: Weights of indexes.

Index	Coefficient of speed variation	Jerk SD	Angle entropy of steering wheel	Maximum depression of the brake pedal	Braking cycles	Heart rate growth rate
e_i	0.948	0.941	0.962	0.957	0.966	0.923
w_i	0.171	0.196	0.125	0.140	0.112	0.255

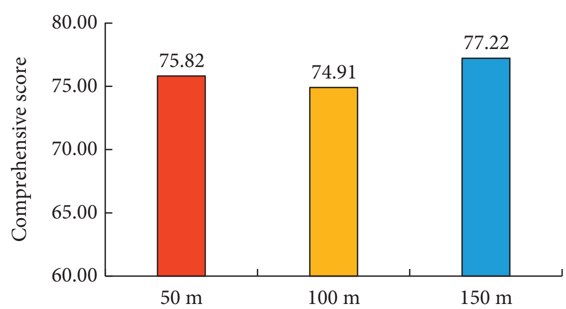


Figure 6: Comprehensive evaluation results of three schemes.

Table 6: Results of fuzzy synthesis evaluation.

Layout plan	Excellent	Good	Medium	Poor
Scheme 2 (install RTCRWS 50 m ahead of the intersection)	0.375	0.186	0.085	0.354
Scheme 3 (install RTCRWS 100 m ahead of the intersection)	0.405	0.059	0.160	0.377
Scheme 4 (install RTCRWS 150 m ahead of the intersection)	0.423	0.186	0.082	0.310

intersection traffic conditions in the direction of information and intelligence.

The major contribution of this study is that a warning effect evaluation model of RTCRWS at rural unsignalized intersections based on entropy weight-fuzzy comprehensive evaluation method was proposed to evaluate the effectiveness of RTCRWS at different locations. It may provide practical references for the research on the reasonable arrangement of traffic safety facilities.

This paper, however, only discussed and compared the warning effects of RTCRWS at 50 m, 100 m, and 150 m ahead of the intersection and drew the conclusions that 150 m before the intersection is the best position of RTCRWS among the three schemes. It has not been studied whether the warning effect of setting up RTCRWS at 200 m or further locations from the intersection is significant. A follow-up study can be carried out to determine the warning effect of RTCRWS in farther locations. Another limitation to the study is that the subjects recruited in the experiment were all middle-aged and young people between the ages of 22 to 55 years, and the conclusions drawn from the study did not apply to the group of elderly drivers. In future research, we can further study the influence of the warning effect of RTCRWS at different locations on the driving behavioral characteristics of elderly drivers, comparing and analyzing the difference of warning effects on different ages. Assuming that there is a significant lag in the response of elderly drivers to RTCRWS, we suggest to provide education for elderly drivers to promote traffic safety awareness.

7. Conclusions

To evaluate the effectiveness of RTCRWS at different intersection locations, the following conclusions are drawn based on analyzing the data collected from the driving simulation experiment:

(i) A general method for the effectiveness evaluation and optimal location determination of RTCRWS at rural unsignalized intersections is proposed and verified.

(ii) The results of the fuzzy comprehensive evaluation showed that RTCRWS is effective in slowing vehicles.

(iii) Among the three schemes, the best warning effect is at 150 m from the intersection, which can effectively improve the driving safety and stability of drivers and enhance their risk perception ability.

It can provide theoretical support for the study of traffic safety at rural unsignalized intersections, to meet the needs of proactive prevention and early warning of traffic crashes.

Data Availability

The data used to support the findings of this paper are available from the corresponding author upon request.

Conflicts of Interest

The authors have no conflicts of interest to declare..

Authors' Contributions

The authors confirm contribution to the paper as follows: research conception and design were done by Fengxiang Guo, Wenchen Yang, and Zhongyin Guo; data collection was done by Changan Xiong and Fengxiang Guo; analysis and interpretation of results were done by Chengyu Hu and Changan Xiong; draft manuscript preparation was done by Chengyu Hu, Fengxiang Guo, and Jaeyoung Lee. All authors reviewed the results and approved the final version of the manuscript.

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