

Research Article

Driver's Attention Allocation and Mental Workload at Different Random Hazard Points on Prairie Highway

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To identify the characteristics of driver's visual perception and measure the mental workload at different random hazard points on prairie highway, an on-road study was conducted with 28 drivers. The I view X HED eye tracker and MP150 multichannel physiological recorder were used to collect the driver's eye movement and ECG data at different hazard scenarios synchronously. The gaze transfer theory and statistical methods were used to make comparative analysis of typical visual and mental workload evaluation indicators of drivers at different random risk points. The results show that no matter what kind of random risk is confronted, the percentage of drivers' fixation duration to the current lane drops, where random risk belongs to increase. The distribution of eye glance transition proportions shows that drivers highly bias their scanning attention by only focusing on transferring between forward and the areas where the random belongs to. Compared with off-road risk points, the driver's gaze transfer is more frequent when facing on-road risk points, and the gaze transfer path is fixed, indicating that on-road risks have higher requirements for drivers' perception and greater information processing load. There are obvious differences in the degree of influence of the types of random risk points on driver's psychology. The heart rate growth rate is the largest when drivers were confronted with overtaking cut-in (37.9%) and forward parking (38%), whereas the index RMSSD changes in the opposite way. It reaches the minimum value when the random risks are overtaking cut-in (22.679 ms) and forward parking (22.907 ms). Meanwhile, the driving speed shows larger fluctuation at risk points on the road. This study reveals that on-road hazards pose greater threats to drivers, and it can contribute to a better understanding of the potential hazards on the prairie highways and provide suggestions for future application of advanced driver assistance systems which can warn drivers about potential hazards.

1. Introduction

Road accidents account for 1.35 million deaths per year, making it the 8th leading cause of death globally [1]. The existence of hazards in the road traffic system is the root cause of road traffic accidents [2]. Due to the uncertainty of emergence of the time and space location, the random risks in the traffic environment subsystem which include random changes in road traffic flow, roadside environment, and climate conditions pose greater security threat [3]. According to the reaction and operation process of the drivers when driving the vehicle, drivers need to continuously obtain effective information from the road driving environment to assist them in making right judgments and decisions and then taking the correct operation. However,

the temporal and spatial uncertainty of random risks in the traffic environment may greatly increase the short-term information perception requirements of drivers, making them getting into the "visual emergency state" [4, 5], and the mental workload will increase instantaneously [6], which will affect the driver's timeliness and accuracy of judgments, decisions, and operations [1, 7–13]. Therefore, research on the visual perception characteristics and mental workload of drivers at random risk points in the traffic environment has important theoretical value and practical significance for further analysis of driving behaviours, traffic accident formation mechanism, and the training of drivers.

Researchers have suggested various classifications for hazards based on required anticipation demands [14]. Crundall et al. defined the term behavioural prediction (BP)

hazards when hazards may be identified directly, environment prediction hazards (EP) when hazards are hidden by a precursor in the environment, and dividing and focusing attention (DF) hazards which contain more than one precursor (which can be either a BP or EP precursor) [15]. Borowsky and Oron-Gilad classified hazards into materialized hazards which required an evasive response, hidden unmaterialized hazards that were potential sources of dangers that were usually obscured by other road users or cultural objects, and potential unmaterialized hazards which were visible sources of danger that could but did not materialize [16]. Guo quantified the risk level in the hazard scenario according to the severity of the traffic conflict and the subjective evaluation of experts [17]. Kahana-Levy et al. related two factors in hazard taxonomy matrix. One factor is whether the hazard has materialized or is yet unmaterialized (i.e., only a potential hazard) and the other is that whether it is visible or hidden. These two factors result in four types of hazards (i.e., hidden materialized, hidden unmaterialized, visible unmaterialized, and visible materialized) [14].

The accurate and efficient perception of road hazards is the most critical skill for safe driving, so hazard perception tests, assessment, and training have garnered much attention of researchers [14]. The hazard perception tests have been developed in a variety of formats and a vast amount of literature is available on drivers' road scanning patterns under traffic conditions with different types of hazards. For example, Huestegge et al. used still images to compare the hazard perception difference between inexperienced and experienced drivers and found that the overall RT was faster for experienced drivers and it was due to faster processing after the initial fixation on the hazard [18]. Scialfa et al. analysed the impact of driving experience on the driver's perception of static risk points [11]. Underwood found that compared with young inexperienced drivers, experienced drivers have a broader spread of search along the horizontal axis that is parallel to the road, from where potential hazards are most likely to appear. In contrast, young inexperienced drivers were found to have a greater spread of search along the vertical axis, from where hazards are less likely to appear [19]. Similar patterns that support Underwood's findings were found in the study of Meir et al. [20]. Meng carried out driving simulation tests in four risk emergency scenarios and the characteristics of the driver's visual attention distribution in different gaze areas in different stress scenes [21]. To explore the visual stress characteristics of drivers in the approaching accident mode, Zhang et al. used eye trackers to carry out real road driving tests on many test drivers. The research results show that the average blink frequency of drivers in response to stress is lower than before the stress response, and the gaze range is wider than before the stress response [22]. Guo studied the internal relationship between behaviour and risk perception of elderly drivers and their differences with young and middle-aged drivers through driving simulation experiments [17]. Accordingly, a growing body of evidence demonstrates that training improves the scanning behaviour of young inexperienced drivers, as reflected in a greater horizontal spread of search and reduced average fixation duration towards hazards [23], and

increases likelihood of scanning areas that contain critical information about potential hazardous situations [24]. Kahana-Levy et al. studied the effectiveness of recurring specific risk scenario training for experienced drivers and novice drivers and found that during training, young inexperienced drivers gradually increased their focus on visible materialized hazards but exhibited no learning curve with respect to hidden hazards [14].

The mental workload of the driver refers to the feeling of tension and pressure when the driver is performing corresponding driving tasks or non-driving-related tasks under the influence of the external traffic environment and the internal cognitive state [25–27]. Waard and Brookhuis discriminated between underload and overload, with the former leading to reduced alertness and lowered attention and the latter leading to distraction, diverted attention, and insufficient capacity and time for adequate information processing, which might cause decision or operator errors, which might lead to traffic accidents [28]. So, measuring the mental workload can provide an indication of the cognitive demands placed on the driver [23, 29].

The measurement methods of the driver's mental workload include the subjective evaluation method, driving task performance method, physiological parameter evaluation method, and so on [30]. The subjective evaluation method is greatly affected by individual differences and cannot evaluate the psychological load in real time, while the driving task performance method is difficult to achieve in the actual traffic environment. The physiological parameter evaluation method indirectly evaluates the mental load of the driver by measuring the changes of the driver's brain electricity, electrocardiogram, eye movement, and other indicators [31]. Studies have found that when a person's mental load changes, the related physiological and psychological indicators will also change, so the physiological parameter evaluation method can provide real-time, objective, and highly sensitive evaluation of mental load [32–34]. Using electrocardiogram, Brookhuis and de Waard studied the difference in the psychological pressure of drivers when driving on a congested circle of urban roads and unobstructed roads and found that in an alert state, drivers are more nervous when driving on the circle than on the highway [30]. In Veltman and Gaillard's study, the sensitivity of physiological measures to mental workload was investigated in a flight simulator, and all measures, which include heart period, continuous blood pressure, respiration, and eye blinks, showed differences between rest and flight and between the pursuit and the tunnel task [35]. Guo et al. studied the physiological characteristics of the driver when the vehicle in front suddenly cuts in based on the driving simulation platform and found that the shorter the cut in distance of the front car, the faster the heart rate growth rate of the driver increases [36]. Meng carried out driving simulation tests in four risk emergency scenarios, and the driver's psychological changes were explored. It was found that different stress scenarios had significantly different effects on the driver's heart rate growth rate [21].

It can be seen from above that most of the research on the perception and mental workload of traffic environment

hazard scenarios mainly focuses on typical risk scenes in the driving environment of expressways and urban roads, and most of the driving tests are carried out based on virtual driving scene platforms. The landscape of typical prairie highway driving environment is significantly different from other road driving environments. It is mainly composed of flat grassland with few humanistic landscapes, and the landscape colour along the road is monotonous. Furthermore, the terrain and morphology changes on the whole line are small, which is represented by the large radius of the vertical curve (the longitudinal slope is mostly concentrated below 2%) and the monotonous horizontal alignment dominated by long straight lines connected with large radius curves (the length of the straight line is about 80%, and the radius of the flat curve is more than 4000 m for more than 60%). So, drivers are in a low-workload driving state most of the time during driving [37]. Meanwhile, since the road affiliated facilities on the prairie highway are insufficient and the settings of which are unreasonable, the drivers may face potential random risks such as animal infestation, roadside parking, parking on the road, the sudden cut in of overtaking vehicles borrowing lanes during driving, and so on. Due to the uncertainty of time and position, the driver must make timely and rapid cognitive efforts to perceive and understand the most critical information in the scene. This may result in instantaneous need of information perception and change of mental workload and increase the probability of driver's failure in judgment, decision making, or vehicle operation manipulation. So, it is of great necessity to do research on the visual characteristics and mental workload of drivers on the prairie highways when the random risks appear. But there is no relevant research on the visual perception characteristics of random risk points in the driving environment of prairie highways so far.

Based on many practical investigations, this paper classifies the risk points of prairie highways according to their state and relative positions and conducts practical driving experiments on prairie highways. The eye movements and ECG data of drivers at typical random risk points are collected. The purpose is to analyse the dynamic visual and mental workload characteristics when the driver passes by the various random risk points. It is hypothesized that the drivers have higher scanning randomness/disorder levels and reallocate their main attention frequently when they are confronted with the sudden appearance of random risks, and the mental workload of them will increase dramatically. It is also predicted that the position and state of the risks will affect the driver's vision characteristics and mental workload.

The remainder of this paper is organized as follows. Section 2 describes the methodology of the test experiment. Section 3 gives the results for eye movement characteristics and mental workload. Section 4 gives a brief discussion of relevant issues. Section 5 draws some conclusions and presents further research.

2. Method

2.1. Participants. The determination of the sample size is the prerequisite for obtaining valid test data. The sample size for this on-road test is calculated based on the index of expected

variance, target confidence, and margin of error. The calculation formula is

$$N = \frac{Z^2 \sigma^2}{E^2}, \quad (1)$$

where N represents the sample size, Z represents the standard normal distribution statistics, E represents the standard deviation, and E is the maximum allowable error. In this paper, the significance level is taken as 10%, then $Z = 1.25$, and the value range of σ is between 0.25 and 0.5. Considering the limitation of the number of subjects in the on-road driving test, the given value of σ is 0.4, and E takes 10%.

Since the minimum sample size is 25 according to equation (1), 28 drivers were recruited as subjects. The age of the subjects was between 36 and 50 years old (mean = 39.5, SD = 5.4), and the driving experience was more than three years (mean = 6.3, SD = 5.2). The participants had statutory driving licenses with normal eyesight and were in good physical and mental state before the test.

2.2. Experimental Equipment. The main equipment of this experiment is shown in Figure 1. According to the investigation of the vehicle types on the test road, 80% of them were passenger cars, so the Passat sedan was selected as the test vehicle as shown in Figure 1(c). The eye movement data acquisition equipment is an I view X HED helmet-mounted eye tracker which can record the eye movement data and eye movement video of the driver's gaze, saccade, and blink in real time (see Figure 1(a)). To ensure the liability and the integrity of the data collection while drivers pass the risk point, the sampling frequency of the eye tracker is set to 200 Hz/s. The eye movement data collection interface is shown in Figure 1(d). The extraction and analysis of eye movement data are carried out using BeGaze2.4 data analysis software that is matched with the eye tracker (see Figure 1(d)). An MP150 multichannel physiological instrument is used in collecting the driver's ECG index (see Figure 1(b)), and the collection interface of it is shown in Figure 1(e). The test vehicle is also equipped with a TES digital handheld luminance meter and noise meter to measure the luminance and noise in the test vehicle to ensure the consistency of the test conditions. Other related auxiliary equipment to ensure the continuity of the test and the complete record of the data include laptop computers, large-capacity batteries, 12 V DC batteries, and so on.

2.3. The Road for Experiment. The test road is a section of provincial highway 101 from Sai Han Ta La to Man Du La Tu, and it is a typical prairie secondary road with a total length of 150 km. The basic road and traffic information of the test road is shown in Table 1.

2.4. The Risk Scenarios in the Driving Experiment. According to the surveys and interviews (traffic management departments and drivers) on the driving environment of typical prairie highways, the random risk points of typical

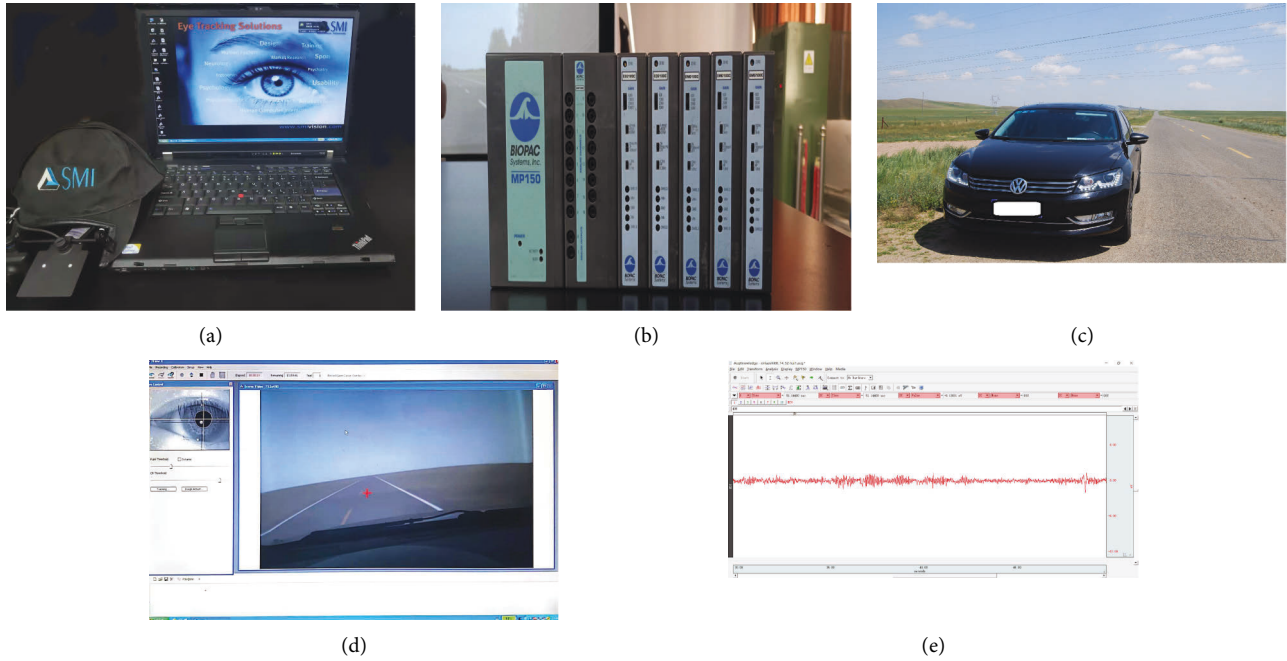


FIGURE 1: Main experimental equipment. (a) I view X HED helmet-mounted eye tracker. (b) MP150 physiological tester. (c) The test vehicle. (d) Eye movement data collection interface. (e) ECG data acquisition interface.

TABLE 1: Road and traffic parameters of test road section.

Road and traffic parameters	Parameter value or characteristic
Design speed (km/h)	80
Number of two-way lanes (lines) and lane width (m)	2/4.5
The ratio of straight-line segment	80%
Road landscape	Plain with micro-hills, monotonous road alignment and landscape
The state of the traffic flow	Free flow
Proportion of large cars	20%

prairie highways are divided into 4 categories based on the relative state and position of them. The result of classification is shown in Table 2, and the schematic diagram of driving risk points is shown in Figure 2.

2.5. Experimental Procedure. To eliminate the influence of external environmental conditions on the equipment and the driver during the test, the test was carried out in the morning when the weather conditions were good, and the luminance was consistent. The test is divided into two stages. The first stage is a 5 min static test and a 5 km driving adaptation training to ensure that the subjects can adapt to the driving environment and equipment to get into a normal driving state. The second stage is the formal test. The subjects are required to complete driving tasks according to daily driving habits and control the driving speed within the maximum speed limit (80 km/h). All the electronic devices in the car that were irrelevant to the test were asked to turned off, and all subjects were informed of the potential risks on the prairie highway and the precautions for safe driving.

The total duration of the test is about 2 h.

2.6. Data Collection and Extraction. After the test, the SMI BeGaze of the I view X HED eye tracker was used to replay the entire eye movement video of each subject, and the eye movement data of the subjects when they confront the 4 types of random risk points were extracted. To eliminate the influence of road conditions and ensure the comparability of visual characteristics and mental workload of drivers, the risk points are all selected on the straight-line sections of the test road. Since the time and place of the risk points are random except for the third type of risk point (the roadside parking, the place of which is the same for all subjects (1 km behind of the toll station)), it is necessary to replay the entire eye movement video of all the subjects to extract the eye movement and ECG data from the random risk points that match the characteristics of the risk point category mentioned above best. According to research by Wang, the duration of random risk scenes ranges from 2 s to 4.2 s with an average value of 3.69 s. Also, considering the hysteresis of the driver's stress response, the interception time of emergency scenes was set as 5s in his study [38]. When studying the visual characteristics of elderly drivers in different levels of risk scenes at intersections, Guo selected the interception time of the risk scene as 10s before the

TABLE 2: The classification of random risk points on prairie highways.

The categories of random risk		States	
		Stationary state	Motion state
Position	On the road	Parking vehicle ahead (PVA)	Overtaking and lane-changing (O&L)
	Roadside (the driving side)	Walking animals (WA)	Vehicle parked aside (VPA)

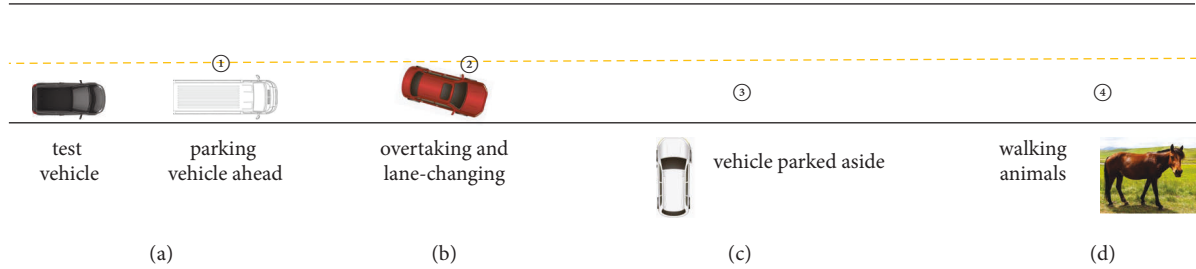


FIGURE 2: Schematic diagram of driving risk area and driving test scene.

intersection [17]. To analyse the visual behaviour performance of the driver passing through the risk point comprehensively, 10s is taken as the time length of the eye movement data interception of the random risk scene in this study, that is, the eye movement data were extracted from 10s before the risk points to the risk points, and 10s eye movement data of a normal straight-line segment with no random risk were interpreted as a blank control.

The Acknowledge software is used to intercept the driver's ECG data in 4 types of random risk scenarios. Considering the lag of the driver's emergency response at the risk point, a total of 15s, from 5s before the risk trigger to 10s after the trigger, is used as the interception time of the ECG data of drivers at random risk points, and the ECG data with no random risk in 15s were interpreted as a blank control synchronously.

3. Results

3.1. Visual Perception Characteristics of Drivers at Random Risk Points. In the study of dynamic visual characteristics of drivers, it is generally considered that gaze and saccade are effective visual behaviours that reflect the collection of road traffic information of the driver and identify the driver's intention and attention allocation, the indicators of which include fixation duration, fixation rate, saccade amplitude, saccade speed, features of viewpoint shift, and so on [14, 32, 39]. So, the fixation duration, fixation times, and gaze transition probability matrixes are used to analyse the visual perception and allocation distribution characteristics of drivers at random risk points.

3.1.1. Division of Areas of Interest (AOIs). To study the driver's attention distribution characteristics and gaze transfer patterns at random risk points, it is necessary to divide the driver's gaze area according to their visual interests. There are many methods for dividing the region of interest, such as mechanical division method, frame-by-frame statistical method, dynamic clustering method, and so

on [17]. By referring to Zhang et al. and Wang and other methods of dividing the gaze point interest area [22, 38], the driver's gaze area is divided into five, which include the current lane, the left area, the right area, the left rear-view mirror, and other areas such as inside and outside of the vehicle. The area that the risk object belongs to is determined according to the relative position of each random risk point, so the division of the driver's gaze interest area and the name of the gaze target contained in each area are shown in Figure 3. It can be seen that the parking vehicle ahead is located in area ①, the vehicle parked on the side of the road and walking animals are located in area ③, and the overtaking cut is mainly located in area ②. The reason for dividing the left rear-view mirror area into one independent area of interest is that the prairie secondary road is a two-way two-lane road. When drivers find that there is risk ahead or on the right and need to make an emergency lane change to the opposite lane, they will check the left rear-view mirror to ensure there is no vehicle behind to pass through the lane, so the left rear-view mirror area is an important area of interest. When the driver passes through a random risk point, the driver's gaze is mainly concentrated in the near area in front of the road, so there is no further division of ①, ②, and ③.

3.1.2. Gaze Characteristics of the Random Risk Points. To compare and analyse the distribution law of the gaze duration of drivers in different areas of interest at various random risk points, the percentage of fixation duration in different areas of interest at each risk point is selected as analysis index.

The percentage of fixation duration is defined as the duration of fixation points in one area divided by the duration of fixation points in all areas:

$$\alpha_j = \frac{\sum_i t_{ij}}{\sum_j \sum_i t_{ij}} \times 100\%, \quad (2)$$

where i represents the number of fixations, j represents the region of interest, α_j refers to the ratio of the driver's gaze duration to the region of interest j , and t_{ij} represents the gaze

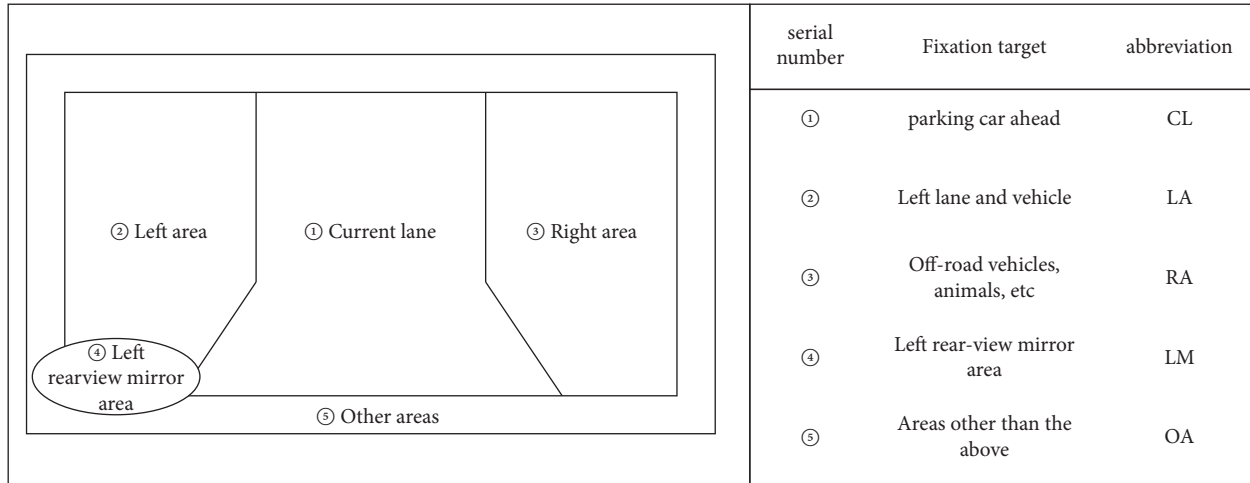


FIGURE 3: Division of area of interest.

duration of the i -th fixation in the region of interest j . The result of the percentage of fixation duration in each AOI at different risk points is shown in Figure 4.

It can be seen from Figure 4 that drivers have the longest fixation duration to the area CL under normal driving conditions which account for 86.8% of the total fixation time. It is followed by a certain degree of attention to the opposite lane of the vehicle in front (LA) which accounts for about 8%. Drivers will also pay attention to the signs that appear on the right side of the road from time to time, so they also have a certain focus (2.5%) on the right side of the road. Besides, the drivers may also shift their sight to other areas (OA) because of the low workload in the environment.

The proportion of the driver's fixation time on the road ahead will drop when random obstacles appear. Among them, the proportion of the gaze in the front of the road is the least when overtaking vehicle cuts in, which accounts for 80.3% and decreases by 7.49% relative to the normal state. This is because the driver needs to spend a certain amount of time paying attention to the overtaking vehicle on the left front, and the length of time duration to the area LA is significantly increased, up to 16%.

When a parked vehicle suddenly appears in front, the driver needs to constantly pay attention to the state of the vehicle in front of the road and to whether there are vehicles coming from the opposite lane or behind borrowing the opposite lane to overtake it. So, compared with the normal driving state, the length of fixation time to the front has decreased, but the decrease rate is not large, about 1.8%. The length of gaze on the left area (the opposite lane) and the left rear-view mirror increased significantly. Compared with parking vehicle ahead, the proportion of the driver's gaze time to the area in front of the road decreases when a vehicle parks aside, while the gaze time to the right area increases significantly, indicating that when there are parked vehicles on the roadside, the driver needs to pay attention to the area where the parked vehicle is located and observe whether there is a possibility of driving into the road.

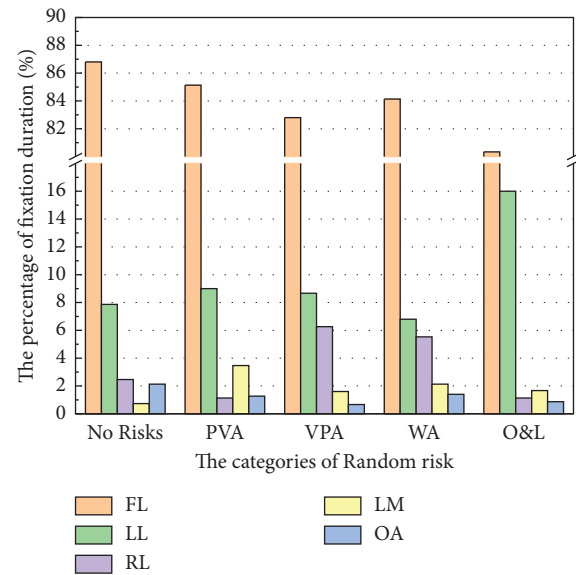


FIGURE 4: Percentage of fixation duration in each AOI at different risk points.

At the risk point of walking animals aside, the driver's gaze time to the area where the roadside animals are located and the area on the left side of the road is longer than that when parking on the roadside, with an increase rate of 13.3% and 27.5%, respectively. This is because the roadside animals are in moving state, and there is the possibility of entering the road at any time. So, it is riskier to the driver, making it take more time to extract information in order to take a braking or steering action. At the same time, when encountering roadside risks, the ratio of the driver's gaze time to the left rear-view mirror is increased to a certain extent compared with the normal driving state, to provide information support for the driver to turn and change lanes to avoid danger. When the driver encounters an overtaking vehicle cut-in, the driver shifts more attention to the left lane, which increases from 7.87% of normal driving to 16%. That means that the motion state of the overtaking vehicle

has a greater impact on the driver, making the driver pay more attention to the moving state of the overtaking vehicle in front of the left.

3.1.3. The Fixation Transfer Characteristics at Random Risk Points. A proportion matrix defined by Wang et al. [40] was used in this study to gather five AOIs (CL, LA, RA, LM, and OA), as shown in Figure 5. The proportion matrix in this study has 25 elements, referring to the 5×5 different consecutive pairs of transitions displayed in Table 3.

Each element is the proportion of saccades moving from location i to j . If $i = j$, it is the proportion of saccades in the location. We let n_{ij} be the number of pairs (i, j) and $\sum_{i=1}^5 \sum_{j=1}^5 n_{ij}$ be the number of total saccades. Then, the proportion of saccades from location of i to location j p_{ij} was defined in

$$P_{ij} = \frac{n_{ij}}{\sum_{i=1}^5 \sum_{j=1}^5 n_{ij}} \quad (i, j = 1, 2, 3, 4, 5). \quad (3)$$

Two essential requirements of the proportion matrix in this study are listed in equations (4) and (5) :

$$0 \leq P_{ij} \leq 1, \quad (i, j = 1, 2, 3, 4, 5), \quad (4)$$

$$\sum_{i=1}^5 \sum_{j=1}^5 P_{ij} = 1 \quad (i, j = 1, 2, 3, 4, 5). \quad (5)$$

The gaze transfer probability of drivers at risk-free and various random risk points is statistically calculated according to equation (4) and the heat map of each scene is plotted and shown in Figure 6.

It can be seen from Figure 6(a) that when driving normally without the influence of random risks, the range of the driver's gaze point is relatively concentrated, and the gaze transfer path is relatively random. In normal driving conditions, drivers are more likely to spend a lot of attention on the area directly ahead. The transition probability within the front area accounts for 31.4%. The probability of gaze transition between the driving lane and the opposing lane is 13.47% and 14.16%, respectively, and there is also a greater probability of transition between the front of the road and the area on the right (10.58% and 9.32%). At the same time, there is also a certain transition probability between other areas (OA) and each area. This fully shows that when drivers are driving freely on prairie roads, due to the single road alignment and small traffic volume, the mental load of the drivers is small. Apart from the attention to the information ahead of the road, drivers will also randomly pay attention to other areas.

As shown in Figure 6(b), when a parking vehicle appeared ahead, the driver's gaze point range is relatively scattered, and the gaze point transfer path is relatively fixed, mainly concentrated among the front of the road, the left side area of the road, and the left rear-view mirror area. The transition probability of the gaze point inside the front of the road accounts for 24.5%, and the transition probability between the front of the road and the left area is 19.21% and 18.26%. There is also a certain amount of

transition between the front of the road and the left rear-view mirror. Compared with the risk-free driving state, the driver's attention to the front of the road decreases, and the transition probability between the gaze point on the left side of the road and the road front area is significantly increased. That is because drivers need to make sure they can change lanes and overtake the parking vehicles ahead timely and safely.

According to Figures 6(c) and 6(d), When there is a parked vehicle or a walking livestock on the right side of the road, the driver's gaze point range and gaze transfer path are similar, which is manifested by a wider range of gaze points and obviously increasing attention to the right side of the road. The probability of the gaze shifting inside the front of the road of these two scenes is 27.49% and 29.12%, respectively. The probability of shifting between the front of the road and the area on the right is similar and greater than when parking ahead or when there is no risk. The degree of attention to the left side of the road declines significantly, and the driver's attention to the left side of the road is slightly higher at the risk points of walking livestock, which means that when encountering risks on the right side of the road, drivers need to constantly pay attention to the environmental information in front of the road and to the roadside risks simultaneously.

When the driver is facing an overtaking cut-in, as shown in Figure 6(e), the gaze transfer law of drivers is like that of the parking vehicle in front, the gaze transfer range is more scattered, and the transfer path is fixed. It is mainly concentrated in the front of the road, the area on the left side of the road, the area on the right side of the road, and the left rear-view mirror. The attention to other areas (OA) is very low. Among them, the probability of transfer within the area in front is 25.6%, which is slightly higher than that of parking ahead. The transfer probability of the gaze point between the front and the right area of the road is 5.53% and 8.32%, respectively, which is higher than the proportion of parking risk points ahead. The transition probability between the front and left areas of the road is 16.94% and 17.17%, respectively, which is slightly lower than the parking vehicle risk point. The transition probability between the front of the road and the left rear-view mirror area is also lower. This is because different from the risk of parking ahead, when facing the front left vehicle to overtake and change lanes to drive back to the front lane, the driver will focus on the area ahead of the road and the overtaking vehicle in front of the left and will also pay attention to the right area to overcome the uncertainty of the vehicle's operating state and take risk-averse maneuver.

3.2. Mental Workload at Different Random Risk Points. Many research results show that the heart rate growth rate and heart rate variability (HRV) of the ECG signal are effective indicators in the driver's mental workload [41–44]. The heart rate growth rate (HRGR) and the RMSSD in the HRV time domain index are selected to analyse the disorder of the driver's HRV index at the risk point.

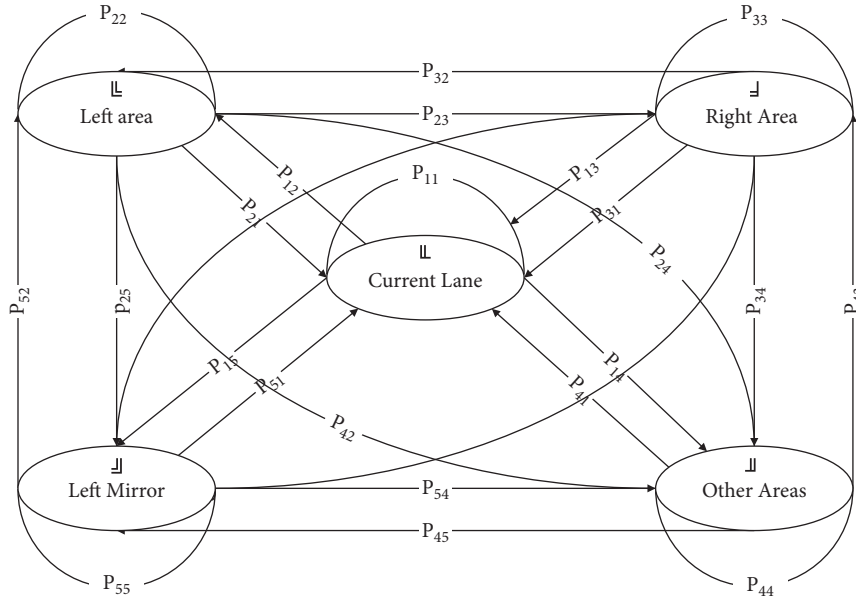


FIGURE 5: A depiction of eye glance pattern with proportions.

TABLE 3: Proportions of gaze transition for the five AOIs.

	CL	LA	RA	RM	OA
CL	P_{11}	P_{12}	P_{13}	P_{14}	P_{15}
LA	P_{21}	P_{22}	P_{23}	P_{24}	P_{25}
RA	P_{31}	P_{32}	P_{33}	P_{34}	P_{35}
RM	P_{41}	P_{42}	P_{43}	P_{44}	P_{45}
OA	P_{51}	P_{52}	P_{53}	P_{54}	P_{55}

3.2.1. *Analysis of Heart Rate Growth Rate (HRGR)*. The heart rate growth rate is defined as the difference between the real-time heart rate during driving and in a calm state divided by the heart rate in a calm state, as shown in the following equation:

$$H_{HRGR} = \frac{(H_{JS} - H_{JC})}{H_{JC}}, \quad (6)$$

where H_{JS} refers to the real-time heart rate value during driving and H_{JC} is the heart rate in a calm state.

One-way repeated measurement analysis of variance was used to analyse the difference of the heart rate growth rate among the different types of random risk points. Table 4 shows the descriptive statistics for HRGR in different risk scenarios. Significant main effect was found for different risk scenarios ($F = 11.65$, $P < 0.05$). The Tukey test was further applied to compare the sources of differences. The results showed that there are significant differences between the random risk of parking and overtaking ahead and no random risk, off-street parking, and walking animals. There is no significant difference between the others. The comparison of each random risk point is shown in Figure 7.

From the results of the analysis of variance and the graph, there are obvious differences in the degree of influence of the types of random risk points on the driver's psychology. Among them, when driving without random

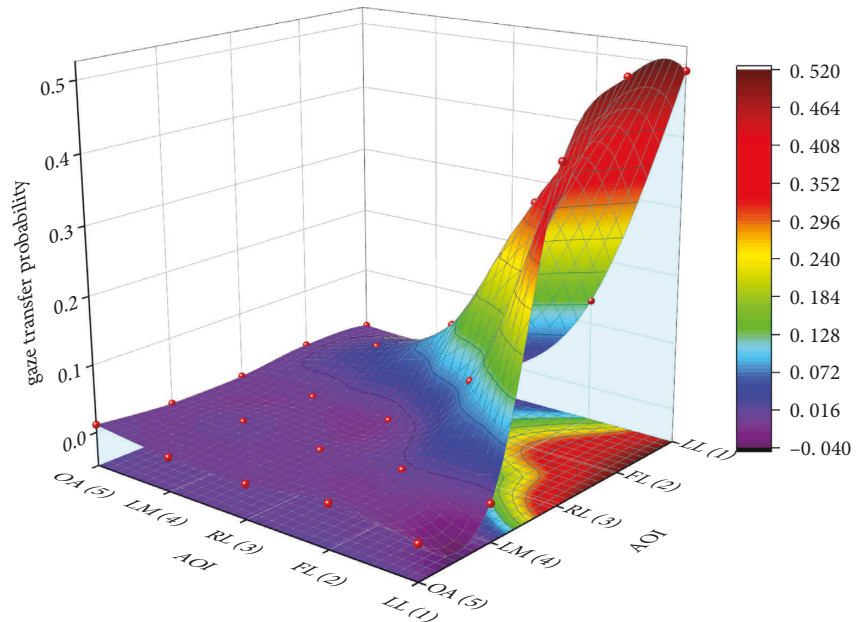
risk, the average value of the driver's heart rate growth rate is the smallest, which is 23%, followed by off-street parking at 25.6% and roadside walking animals at 28.9%. The largest growth rate is overtaking cut-in (37.9%) and forward parking (38%). It shows that drivers are more alert to the emergence of random risks on the road. That is because both the PVA and O&L risks occurred in the front of driving road, which have a direct impact on the driver's decision making and driving behaviour. If drivers do not respond in time or operate improperly, it may result in an accident. The mental workload of drivers at the WA and VPA risk points is lower, and there was no significant difference between them; this is because both the risks are beside the road, which are not direct threats to the drivers, and the drivers have relatively more time to make decisions and take actions. But they are larger compared with normal driving because drivers need to monitor the status of the two risks, which may increase the mental workload of them.

3.2.2. *Comparative Analysis of RMSSD*. RMSSD refers to the root mean square of the difference between two adjacent R-R intervals, which is used to estimate the components of short-range HRV. The lower the RMSSD value, the higher the mental load. It is calculated as follows:

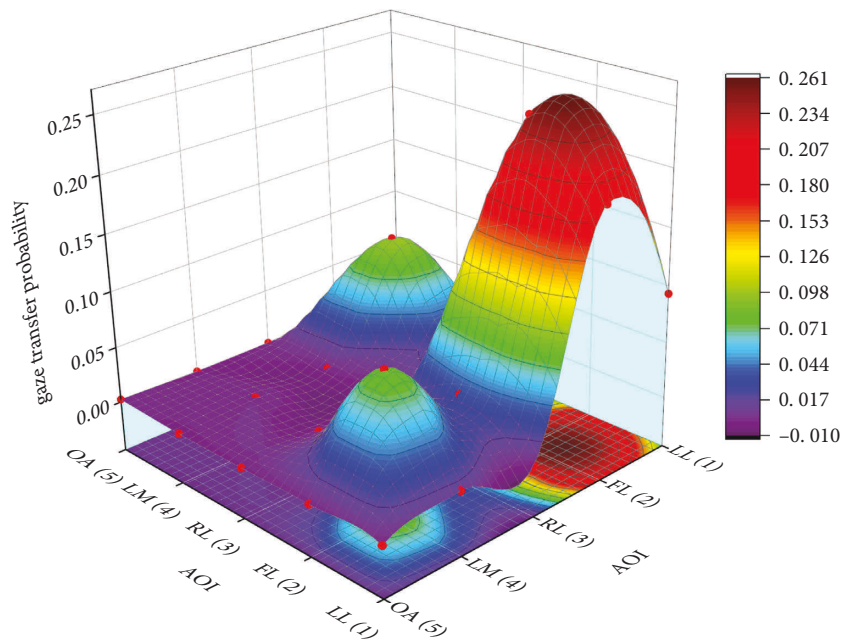
$$RMSSD = \sqrt{\frac{1}{N-1} \sum_{i=1}^{N-1} (t_{RR,i+1} - t_{RR,i})^2}, \quad (7)$$

where $t_{RR,i}$ and $t_{RR,i+1}$ are the lengths of two adjacent sinus cardiac cycles.

Table 5 shows the descriptive statistics for RMSSD in different risk scenarios. Significant main effect was found for different risk scenarios ($F = 11.65$, $P < 0.05$). The Tukey test was further applied to compare the sources of differences, and the results showed that there were significant differences



(a)



(b)

FIGURE 6: Continued.

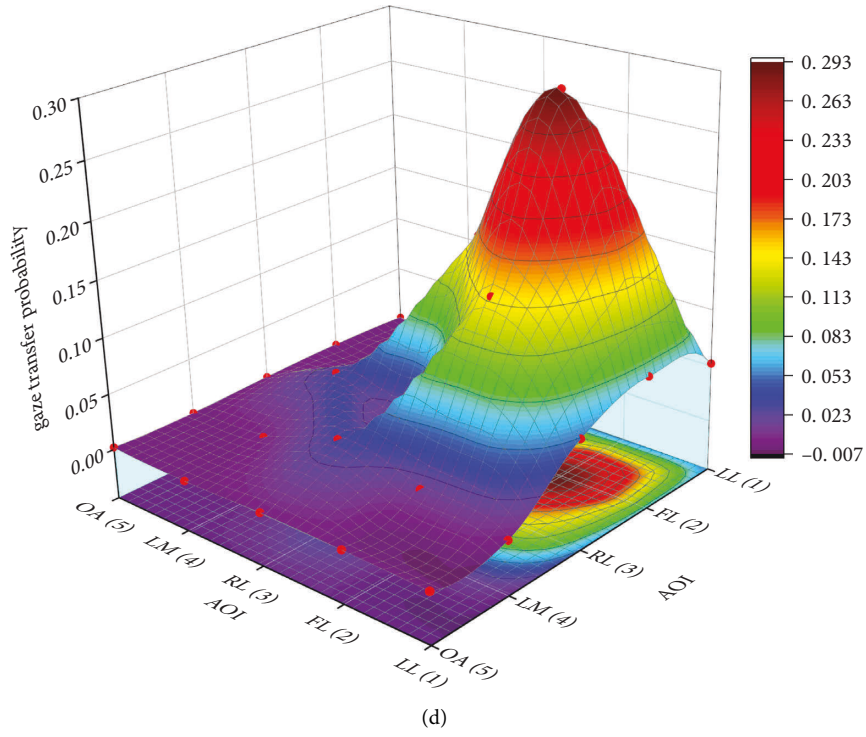
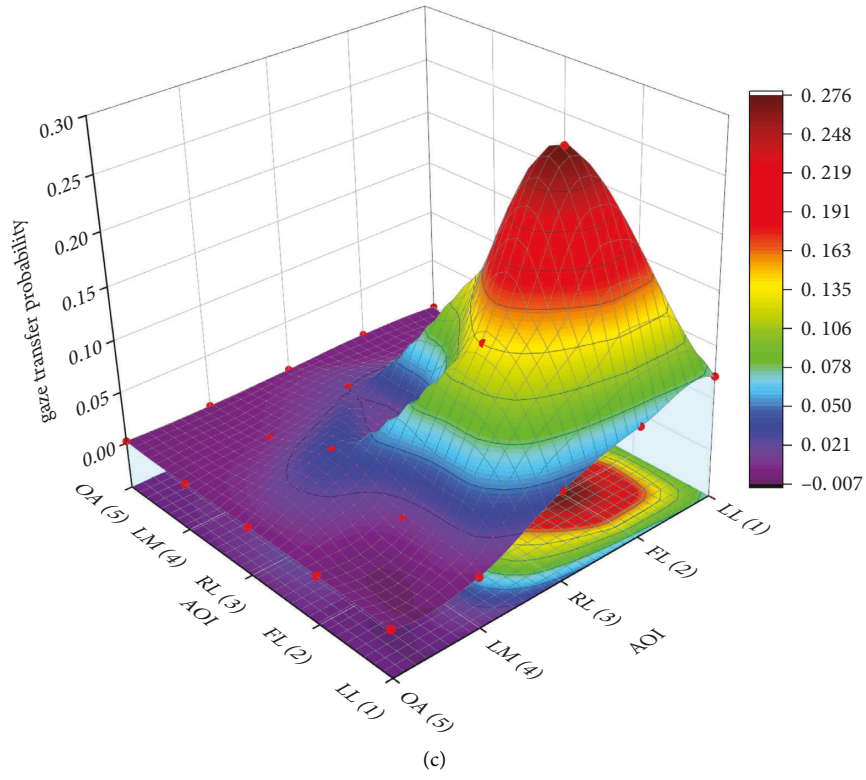


FIGURE 6: Continued.

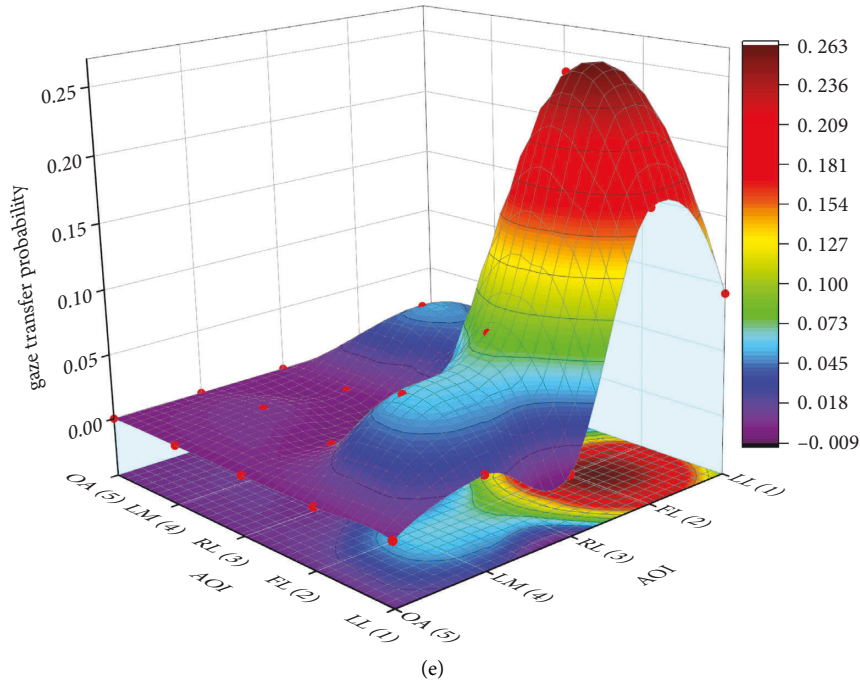


FIGURE 6: Fixation transition probability heat map at random risk point. (a) No risks. (b) PVA. (c) VPA. (d) WA. (e) O&L.

TABLE 4: Descriptive statistics (mean and standard deviations) for HRGR measure in different risk scenarios.

HR variable	Driving scenarios										P value
	No risks		Parking vehicle ahead		Vehicle parked aside		Walking animals		Overtaking and lane-changing		
	Mean	Std.	Mean	Std.	Mean	Std.	Mean	Std.	Mean	Std.	
HRGR (%)	23.045	1.762	38.053	4.768	25.687	2.282	28.931	3.114	37.975	3.779	<0.05

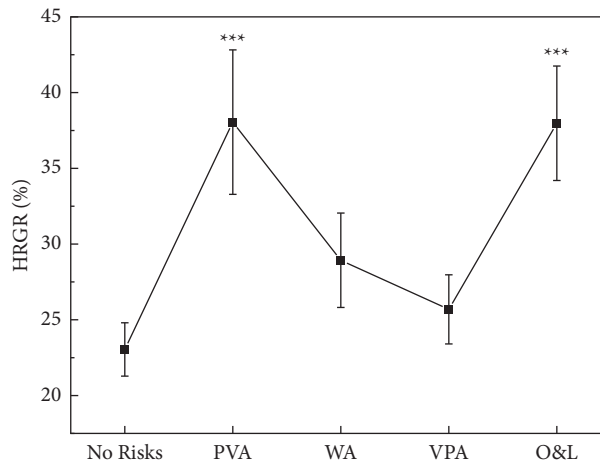


FIGURE 7: Comparison of heart rate growth rates of drivers at different types of random risk points.

between the random risk of parking and overtaking ahead and no random risk, off-street parking, and walking animals. There is no significant difference between the others. The comparison of each random risk point is shown in Figure 8.

From the results of the analysis of variance and Figure 8, there are obvious differences in the degree of influence of the

types of random risk points on the driver’s psychology. Among them, when driving without random risk, the average value of the driver’s RMSSD is the largest, followed by WA and VPA, and it is relatively small at PVA and O&L risk scenarios. That means drivers’ mental workload was higher at PVA and O&L risk points, which is consistent with the

TABLE 5: Descriptive statistics (mean and standard deviations) for RMSSD measure in different risk scenarios.

HRV variable	Driving scenarios										P value
	No risks		Parking vehicle ahead		Vehicle parked aside		Walking animals		Overtaking and lane-changing		
	Mean	Std.	Mean	Std.	Mean	Std.	Mean	Std.	Mean	Std.	
RMSSD (ms)	31.071	1.34	22.907	1.130	28.221	1.503	27.000	1.450	22.679	1.331	<0.05

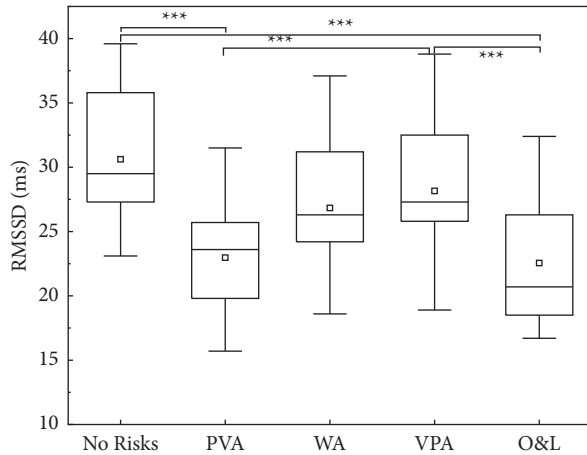


FIGURE 8: Comparison of driver's time-domain index RMSSD at different types of random risk points.

analysis of heart rate growth rate above. So, the position of the risks is an important factor of drivers' mental workload, whereas the influence of the state of the risks is not obvious.

3.3. Speed at Different Random Risk Points. According to the human information process model, drivers' behaviours come from their perception of various external factors, as well as cognitive processing and behavioural decision making based on the perceived content [45]. Since the choice of driving speed has been considered as a critical determinant of crash involvement, the driving speed when drivers approached the risks point was selected.

To analyse the distribution of speed at various risk points, the speed was divided in 5 km/h classes and Gaussian curve was obtained. As shown in Figure 9, the distribution curve of speed at PVA and O&L risk points was inclined to the left low-speed area, whereas they tended to the high-speed area on the right at WA and VPA risk points. Also, there were many intermediate speed frequencies at both WA and VPA risk points, but the lower and higher speed frequencies were more at PVA and O&L risk points. The change curve of speed at different risk points shown in Figure 10 verified this. Drivers' speed decreased more at PVA and O&L risk points, which were about 20 km/h at the risk point, whereas they were more than 30 km/h at the WA and VPA risk points. Both the positions of PVA and O&L risks were directly in front of the driving lane, and they had greater impact on drivers' behaviour. That was because drivers needed to take immediate actions to avoid direct potential collisions, which was illustrated by larger fluctuation of driving speed at on-road risk points.

4. Discussion

Visual attention is directly associated with crash risks [46, 47]. This study analysed both drivers' fixation characteristics and glance transition patterns while driving. The results of driver's visual perception characteristics support the hypothesis that the divers have higher scanning randomness/disorder levels when they are confronted with the sudden appearance of random risks. No matter what kind of random risk is confronted, the percentage of drivers' fixation duration to the current lane drops, whereas the percentage of the areas where the random belongs to increases. Many studies have confirmed this result. Li et al. [48] found that in various emergency scenarios, the average percentage of the driver's gaze points on the main area used to obtain information is up to 60%–70%, while the average fixation point percentage of the auxiliary area is about 10%–20%.

The glance transition patterns among different AOIs were analysed by proportion matrix and it indicated ratios of changes for drivers' eye movements during visual scanning among the five main locations (i.e., CL, LA, RA, LM, and OA). The distribution of eye glance transition proportions showed drivers highly biased their scanning attention by only focusing on transferring between forward and the areas where the random belongs to. The area in front of the road is the main area for drivers to obtain information when there is no risk, whereas the driver's attention to the area in front of the road decreases once risks suddenly appear on or beside the road, which is manifested by the significant increase in the probability of transition between the front of the road and the areas of the risks. That means that once a risk point is encountered, the driver needs to quickly perceive the change in the risk point information to make correct judgments and take appropriate countermeasures. Compared with off-road risk points, the driver's gaze transfer is more frequent when facing on-road risk points, and the gaze transfer path is more and fixed, indicating that on-road risks have higher requirements for drivers' perception and greater information processing load. It verifies the hypothesis that the location of the risk point will affect the driver's visual transfer characteristics, and the risk point on the road has higher requirements for the driver's visual perception and brings a greater visual load. The glance transition patterns are almost indistinguishable between the obstacles with different states. Unlike the location of the risk point, the state of the risk point has little effect on the driver's visual transfer characteristics. No matter it is static or in motion, the visual transfer characteristics of drivers are almost the same. The glance transition proportion matrix was first defined by Wang et al. to compare the difference of transferring of eye glance between distracted driving and normal driving. Their

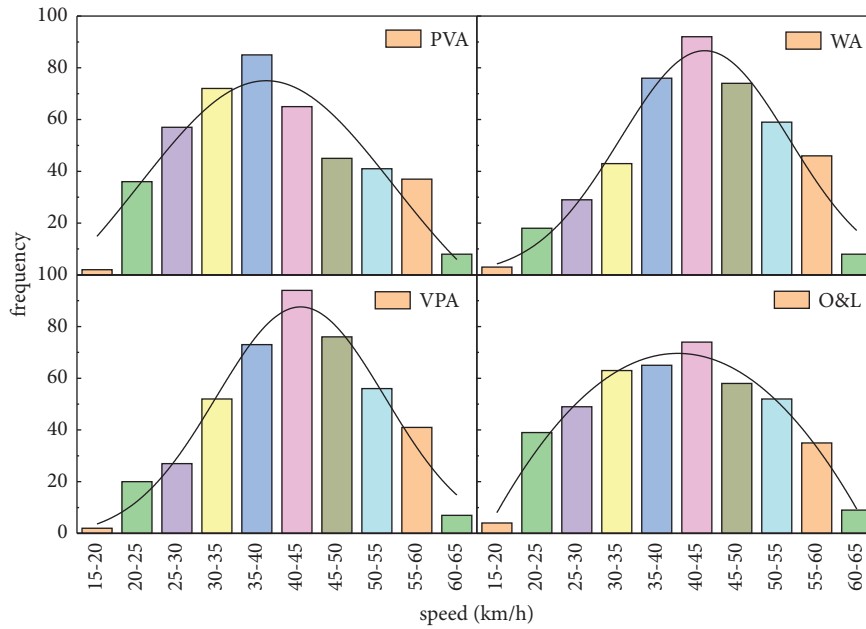


FIGURE 9: Distribution of speed at different types of random risk points.

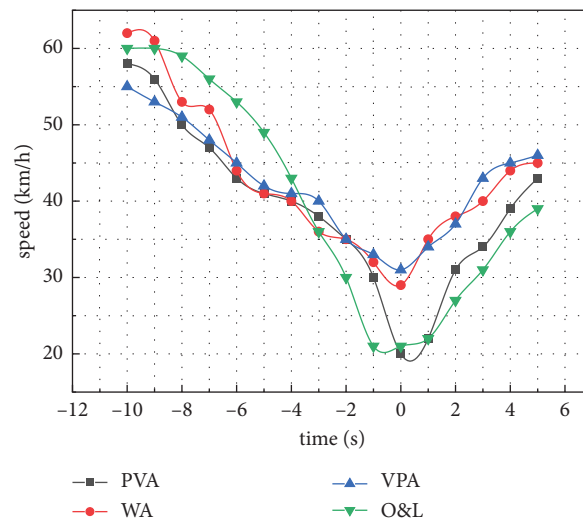


FIGURE 10: Speed change curve at different types of random risk points.

result showed that drivers focused on transferring between forward and phone locations with 85.7% of the time when engaged in distracted driving. Significantly lower proportions of scanning between forward area and mirrors with a value of 8.3% under distracted driving were observed [40]. The reason was that drivers reallocated their main scanning dimensional attention from surrounding areas towards phone area when engaging in visual-manual tasks, whereas drivers' attention was allocated more to the areas where the risks belong to in our study because they needed to get more information about the state of the risks and the relative distance of risk points in order to make decisions and take actions.

Some studies have shown that the effect of different types of traffic conflict on the physiological characteristics

of drivers is different [36, 49, 50]. Phyu et al. investigated the effect of roadway conditions on driving stress in Myanmar by using heart rate variability (HRV) and found that highly crowded places and those requiring attention are the most stressful segments along the roadway for drivers [49]. Liu et al. research on the mental workload of drivers in the condition of vehicle emergency avoidance found that with the increase of the driving speed and the decrease of the distance from the obstacle, the variation of the driver's heart rate increases and the psychological load increases [50]. Guo et al. study on the stress physiological characteristics when front vehicle cuts in suddenly shows that while speed is 100 km/h, with decreasing of cut in distance from 55.6 m to 27.8 m, the average heart rate growth increases from 16.21% to 23.27, and HRV LF

decreases correspondingly [36]. The result in this paper is consistent with these studies. In this study, there are obvious differences in the degree of influence of the types of random risk points on the driver's psychology. The heart rate growth rate is largest when drivers were confronted with overtaking cut-in (37.9%) and forward parking (38%), whereas the index RMSSD changes in the opposite way. It is the smallest when the random risks are overtaking cut-in (22.679 ms) and forward parking (22.907 ms). So, it indicated that drivers are more alert to the emergence of random risks on the road no matter it is static or in motion. As far as the driving speed is concerned, the speed distribution at different risk points was different, and the position of the risk points showed obvious influence on the driving speed of drivers with larger speed changes at risk points at the road. The result was consistent with the larger mental workload at both PVA and O&L risk points on the road, and it revealed that drivers needed to pay more attention to potential threats in the front of the driving lane to prevent direct collision, which resulted in larger changes in mental workload and driving behaviours. The results of speed choice in this study are consistent with other studies [51, 52]. Wang et al. did study on hazard handling training method for novice drivers and found that the trained drivers anticipated potential hazards in advance to a larger extent than the untrained, which was indicated by both earlier speed reduction and subjective self-report data when approaching the hazards. This training method can be used to the handle these random risks on the prairie highways in future.

5. Conclusions

This paper compares and analyses the gaze and transfer characteristics of drivers at different types of risk points on prairie highways through actual driving tests and draws the following conclusions:

- (1) During normal driving, drivers tend to pay a lot of attention to the area directly in front of the road, but once a random risk occurs, the time of their gaze on the area where the risk point is located will increase. The road area is used as the main information acquisition area, and the area where the risk point is located is also selected as an auxiliary area to supplement the information acquisition, to assist them in making correct decisions.
- (2) The distribution of eye glance transition proportions showed that drivers highly biased their scanning attention by only focusing on transferring between forward and the areas where the random belongs to. Compared with off-road risk points, the driver's gaze transfer is more frequent when facing on-road risk points, and the gaze transfer path is more and fixed, indicating that on-road risks have higher requirements for drivers' perception and greater information processing load. The glance transition patterns are almost indistinguishable between the obstacles with different states.
- (3) The influence of different types of random risk points on driver's psychology varies. The heart rate growth rate is largest when drivers were confronted with overtaking cut-in and forward parking, whereas the index RMSSD changes in the opposite way. It is the smallest when the random risks are overtaking cut-in and forward parking. The driving speed, meanwhile, shows larger fluctuation at on-road risk points. This indicates that drivers are more alert to the emergence of random risks on the road no matter it is static or in motion.

This study revealed that on-road hazard poses greater threats to drivers, and it can contribute to a better understanding of the potential hazards on the prairie highways and provide suggestions for future application of advanced driver assistance systems which can warn drivers about these potential hazards. A limitation of the present study is that it only emphasizes on the visual and cognitive aspects and the driving speed of drivers; further research is needed on other driving maneuver behaviours of drivers to illustrate the influence of visual and cognitive state on the drivers at these random hazard points. Furthermore, previous studies showed that age (young, middle-aged, and older) would influence drivers' visual scanning and mental workload simultaneously; also, some hazard handling training methods were explored and demonstrated to be effective in improving the driving behaviour at risk points. So, future efforts would be concentrated on these aspects [53].

Data Availability

Since the corresponding author is a Ph.D. candidate, the data used to support the findings of this study are available from the corresponding author upon request after the author gets her doctor's degree.

Conflicts of Interest

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

Acknowledgments

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