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# Freeway Traffic Safety Evaluation Using Virtual Reality: Focus on Compound Curve

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**Abstract:** The traditional method of designing freeway geometric characteristics may not well consider traffic safety and evaluation problems associated with vehicle, driver, road, and environmental features. This paper looks into accident-prone compound curves and puts forward a traffic safety evaluation method that can comprehensively assess various influencing factors. This method integrates driving simulation and Virtual Reality (VR) technology. Methodically, this paper first used three-dimensional (3D) design software to build the digital model and spatial scene model of the compound curves from the aspects of geometric structure, spatial characteristics, terrain information, and so on. Next, drivers were invited to conduct a series of driving simulation experiments upon the human–computer interaction safety experience platform, and driver physiological data and vehicle driving information collected. Last but not least, the mean values of heart rate changes, steering wheel angle changes, and driving trajectory changes were derived to synthesise the comprehensive traffic safety evaluation framework. Based on the analysis of the results of the orthogonal test, select the road plane design indicators that have a significant impact on the traffic safety evaluation, and carry out regression analysis. The research shows that the novel traffic safety evaluation method integrating with VR technology can comprehensively consider various influencing factors, and designers can dynamically adjust the design metrics according to the traffic safety level.

**Keywords:** freeway geometric characteristics; traffic safety and evaluation; compound curves; VR; evaluation framework

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## 1. Introduction

In the last decade, the Chinese government has mandated the use of digital technology in delivering its road infrastructure projects for the sake of safety, quality, and efficiency. China's freeway networks sprawl across a large portion of its territory. Traffic safety evaluation on highways is an important topic in the transportation research. In particular, highways in mountainous areas comprised of compound curves are likely to be accident-prone [1]. Horizontal alignment indices of the compound curves section must meet the design and safety requirements [2]. However, the current research mainly addresses the applicability of certain design indices in this context, such as intermediate straight line length, transition curve form, so on so forth.

To sum up, the overall safety of highway alignment, as an important traffic safety factor, should be considered through the design and operation of highway projects. However, the current design method of the compound curves section is a static design method, in which the dynamic characteristics affecting the traffic safety are not fully considered in the selection of indicators. The Virtual Reality (VR) visualisation has a great potential to the design safety of compound curves. Based on information modeling technology and virtual driving simulation, VR can integrate spatial alignment parameters, traffic signs, road and terrain features, as well as other information into a multi-dimensional visualisation platform. It can achieve the interconnection of information among multiple disciplines and realise multi-dimensional information simulation by using simulation glasses and driving simulators. Based on the data generated in the evaluation process of the compound curves, closed-loop feedback and optimisation were then performed. In this paper, two common compound curves types are studied, which are the intermediate straight type and compound curves type. Based on the compound curves VR mapping and driving simulation platform, different drivers are invited to conduct driving simulation tests. Intelligent detection equipment is used to monitor the driver's relevant psychophysiological indicators in real time, which are used to feed back the compound curves safety design. Finally, based on theoretical analysis, the traffic safety evaluation models of the two types of compound curves are established.

## 2. Literature Review

This research involves two kinds of the compound curves. One is to connect two circular curves with the straight lines, the other is to use spiral curve to connect two circular curves in the same direction. The former is called straight-line section, and the latter is called oval curve (see Figures 1 and 2).

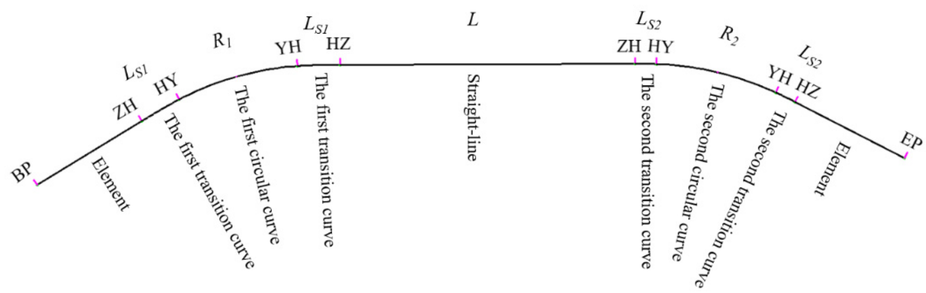


**Figure 1.** Compound curve with straight section.

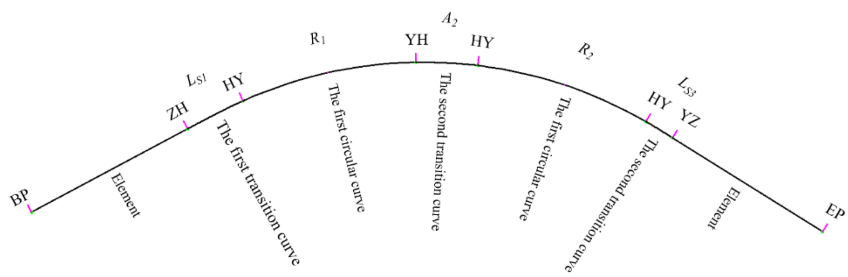


**Figure 2.** Compound curve with transition curve section.

The research summarises the design indexes research and traffic safety evaluation of the compound curves section. Li (2015) concluded that the short intermediate straight line between the circular curves in the same direction was easy to make the driver regard it as a broken back curve. Furthermore, in order to avoid the problem of short intermediate straight line, the convolution line was often used to connect two circular curves in the same direction to form an oval curve [3]. In 2019, Pan Yongzhou pointed out the oval curve would be adopted mainly when the terrain was limited as the problem of complex line shape, cumbersome calculation, and relatively strict composition conditions [4]. At present, the selection of the two compound curves by the design unit mainly depends on the road network planning, engineering scheme, investment, safety, environment and other factors of the project, and the rationality of the actual design indicators are mainly checked in accordance with the specifications.

At present, there are relatively few studies on the road in the compound curves. For the straight-line section, the research mainly focuses on the intermediate straight line length between two circular curves. Different countries have different regulations on the shortest intermediate straight line length. In American AASHTO, the length of the shortest intermediate straight line is mainly calculated based on the length of horizontal curve. It stipulates that the length of the minimum horizontal curve on the main highway is three times the design speed (km/h), and the length of the minimum horizontal curve on the freeway is six times the design speed (km/h). While designing, the curve forms that may cause back breakage should be avoided as far as possible [5]. In Japan, relevant studies mainly rely on the perspective view formed by the compound curves to specify the shortest intermediate straight line length, and finally determine the conclusion that the intermediate straight line length should not reach 500~700 m [6]. In Germany, relevant departments stipulate that intermediate straight line should be avoided to connect two circular curves in the same direction on class A roads. If they cannot be avoided, the shortest length should be six times the design speed (km/h) in order to ensure the stability of driving [7]. In China, Design Specification for Highway Alignment requires that the straight-line length (m) between two circular curves in the same direction should not be less than six times the design speed (km/h). This provision mainly refers to Germany's consideration of the shortest intermediate straight line length [8]. Domestic scholars have considered the length of the intermediate straight line from different angles. In 2012, Zhang Rongjie et al. derived the shortest intermediate straight line model between curves in the same direction theoretically to meet the comfort requirements of superelevation transition, acceleration and deceleration based on the driving dynamics, and concluded that the shortest intermediate straight line length decreases with the increase of circular curve radius [9]. In 2017, Qin Shengke proposed the minimum length of intermediate straight line based on running speed. The shortest intermediate straight line length model is established based on the two stages of vehicle acceleration and deceleration, and proposed that the shortest intermediate straight line length will be affected by the grades of the road [10]. In 2019, Yang Fan established the minimum intermediate straight line length model between curves in the same direction based on the effective field of view and running speed respectively [11] (see Table 1).

**Table 1.** Typical mathematical model of minimum straight length of highway.

| Auther | Mathematical Models |
|---|---|
| Qin Shengke | $L_v = \frac{V_{max}^2 - V_1^2}{25.92(a_1+gi)+\frac{V_{max}^2-V_2^2}{25.92(a_2+gi)}}$ |
| Yang Fan | $L_v = \frac{V_{max}^2 - V_1^2}{25.92a_1} + \frac{V_{max}^2 - V_2^2}{25.92a_2}$ |

where: $L_v$—minimum straight segment length; $V_{max}$—Maximum running speed of vehicles in straight line section; $V_1$—vehicle driving speed at the end point of front end curve of straight line section; $V_2$—vehicle driving speed at the starting point of the curve at the rear end of the straight section; $a_1$—vehicle acceleration; $a_2$—vehicle deceleration; $g$—gravitational acceleration; $i$—grades.

The research on oval curves mainly focuses on the coordinate calculation and other issues in the actual measurement process. In 2000, Xing Xile calculated the coordinates of any point on the transition curve based on the curvature estimation method [12]. In 2021, Pan Binghong et al. analyzed the driving stability of K-curve and clothoid on an oval curve [13]. Some scholars have carried out a qualitative study on the rationality of the regulations on an oval curve in the specification. In 2008, Shi Qiang et al. studied the rationality of some provisions in the specification and put forward suggestions [14]. In 2020, Chang Yuhong firstly considered the safety evaluation of oval curves, mainly discussing the qualitative and quantitative evaluation factors that should be paid attention to in the evaluation, and put forward some safety measures according to the corresponding characteristics [15].

The road safety evaluation mainly depends on the relevant standards or guidelines to check the rationality of the design indexes. Some scholars gradually began to evaluate the traffic safety from different angles according to the driver's psychophysiological characteristics, vehicle driving characteristics and road accident data characteristics. In

1998, Richter et al., taking the change rate of road curvature as the independent variable, obtained a comprehensive evaluation method of physiological indicators of drivers based on the reliability analysis [16]. In 2001, Myungsoon Chang et al. obtained in their research that the driver will remain nervous for 4 s after entering the merging area, and then obtained the length range of the relatively dangerous road section [17]. In 2002, Laura Eboli et al. proposed the 85th percentile running speed in the study to study the safety level of curve sections, and established the correlation model between the running speed and road alignment [18]. Moreover, the indicators of the safety evaluation system are highly subjective and less comprehensive. In short, the current traffic safety evaluation mainly uses the principle of typical driving dynamics to establish the correlation between an evaluation index and road alignment after establishing a simulation model. The research on the safety evaluation of the compound curves section mainly aims at the influence of the characteristics of driver, vehicle and road on the traffic safety, and cannot take into account multiple influencing factors. Moreover, most of the relevant safety impact factors are based on qualitative descriptive words, lacking quantitative evaluation consideration.

On this basis, this paper introduces multi-dimensional visual information modeling technology and simulation technology, establishing a driving simulation experiment platform. Then drivers evaluate the handling safety of the compound curves section according to their own driving experience. Road designers and consultants evaluate the safety of the compound curves section from the perspective of professional indicators according to the multidimensional visual information model. Finally, this study considers the driving characteristics with the handling stability and the driver characteristics with the handling comfort, and carries out the traffic safety evaluation on the two compound curves sections by establishing comprehensive evaluation indicators.

## 3. Influencing Factors of Traffic Safety in the Compound Curves Section

### *3.1. Summary of Accident Type Distribution in the Compound Curves Section*

According to the turning direction of the adjacent circular curve, the horizontal curve can be divided into the same direction curve and the reverse curve. The forms of the same direction curve mainly include oval curve, C-shaped curve, convex curve and the same direction curve section connected by an intermediate straight line. As the conditions for the use of C-shaped curve and convex curve are only adopted when the route is strictly restricted by terrain, the C-shaped curve and convex curve are usually not designed as the same-direction curve in a high-grade highway. In this paper, two freeways that have been completed and operated are collected as the research objects, namely NQ Freeway and SX freeway. This paper takes six times the running speed as the dividing point of the same direction curve and twice the running speed as the dividing point of the reverse curve. The specific statistical results are shown in the table below (Table 2).

**Table 2.** Statistics of curve section length of investigated freeway project.

| Project | Type | Length (km) | Length Proportion |
|---|---|---|---|
| SX Freeway | same direction curve | 19.740 | 28% |
| | reverse curve | 30.191 | 44% |
| | overlapping section | 6.025 | 9% |
| NQ Freeway | same direction curve | 47.047 | 34% |
| | reverse curve | 77.263 | 57% |
| | overlapping section | 23.044 | 17% |

From Table 2, it can be seen that in the two projects, curve sections account for a relatively high proportion of the total length of the project, which indicates that curve sections tend to account for a higher proportion in freeway alignment design.

This study collects the accident data of the above two operating expressways as the basis, which are respectively the accident data of SX Expressway from October 2017 to October 2019 and the traffic accident data of NQ Expressway from January 2018 to June 2021. Among them, there are 69 data of accident types completely recorded in the same direction curve section of SX Expressway, 140 data of accident types completely recorded in the reverse curve section, and 27 data occurring in the overlapping section of the same direction curve and reverse curve; in the NQ Expressway, 318 accident types were completely recorded in the same direction curve sections, and 704 accident types were completely recorded in the reverse curve sections. There were 63 accident types occurring in the overlapping sections of the same direction curve and reverse curve. The proportion of traffic accidents within the overlapping sections of the two highways under investigation does not exceed 15%, and even only accounts for less than 6% in NQ Expressway. Therefore, it can be considered that the overlapping sections are not the accident prone points of curve sections.

In order to compare the level of traffic accidents in different curve sections, this study first makes preliminary statistics according to the distribution of accident severity, using the non single vehicle accident rate method as an indicator (see Table 3). This is because in expressway traffic accidents, the severity of the accident can be preliminarily evaluated according to the number of affected vehicles involved. The more vehicles involved, the greater the loss and the more serious the consequences. Therefore, the next step is to extract the data that the accident types in the accident account records are divided into, namely, two vehicle accidents and multi vehicle accidents. The calculation method of non-single-vehicle accident rate is as follows.

$$\beta = \frac{m+n}{M} \tag{1}$$

where: $\beta$—non single vehicle accident rate; $m$, $n$—Number of double vehicle accidents and multiple vehicle accidents; $M$—total accidents;

**Table 3.** Non single vehicle accident rate in different curve sections.

| Project | Same Direction Curve | | Reverse Curve | |
|---|---|---|---|---|
| | $m + n$ | $\beta$ | $m + n$ | $\beta$ |
| SX Freeway | 10 | 14.5% | 16 | 11.4% |
| NQ Freeway | 101 | 31.8% | 191 | 27.1% |

It can be seen from the Table 3 that the compound curves section has a higher possibility of multi vehicle accidents and more serious traffic accidents. In order to further quantify and compare the severity of traffic accidents in different curve sections, this paper uses the equivalent accident rate to evaluate the accident level of the investigated full-length section, the compound curves section and the reverse curve section. The indicator of equivalent accident rate is mainly used to quantify the number of casualties in traffic accidents and to characterize the severity of traffic accidents by multiplying them by different weights. In 2011, Li Zhizhong discussed the different weights of the injured person number [19]. The comparison results of the equivalent accident rates of the two projects are shown in the figure below (Figure 3).

Through the analysis and comparison of design data and accident data of curve sections in SX Freeway and NQ Freeway, the non single vehicle accident rate in the compound curves section is higher than that, in the reverse curve section, indicating that the traffic accident in the compound curves section is more likely to involve multiple vehicles. Further sort out the accident patterns of the two freeways, there are four main accident forms in the investigated compound curves section, namely rear end collision, single vehicle accident, mechanical failure and others. See the figure below (Figure 4) for the percentage of specific accident form distribution.

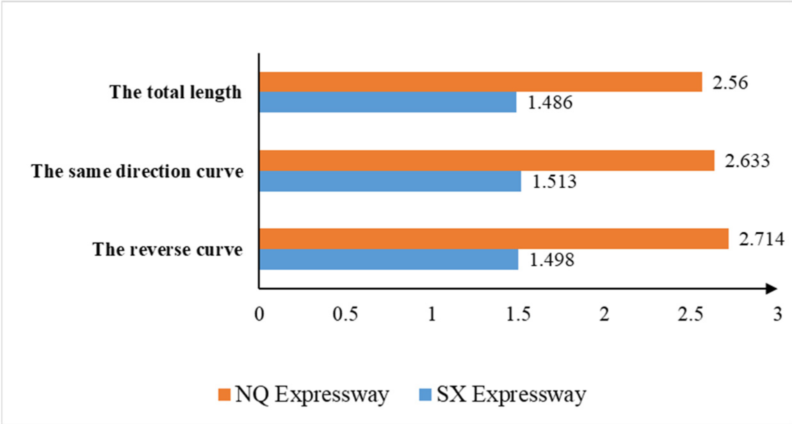


**Figure 3.** Comparison results of equivalent accident rates of different sections of freeway.

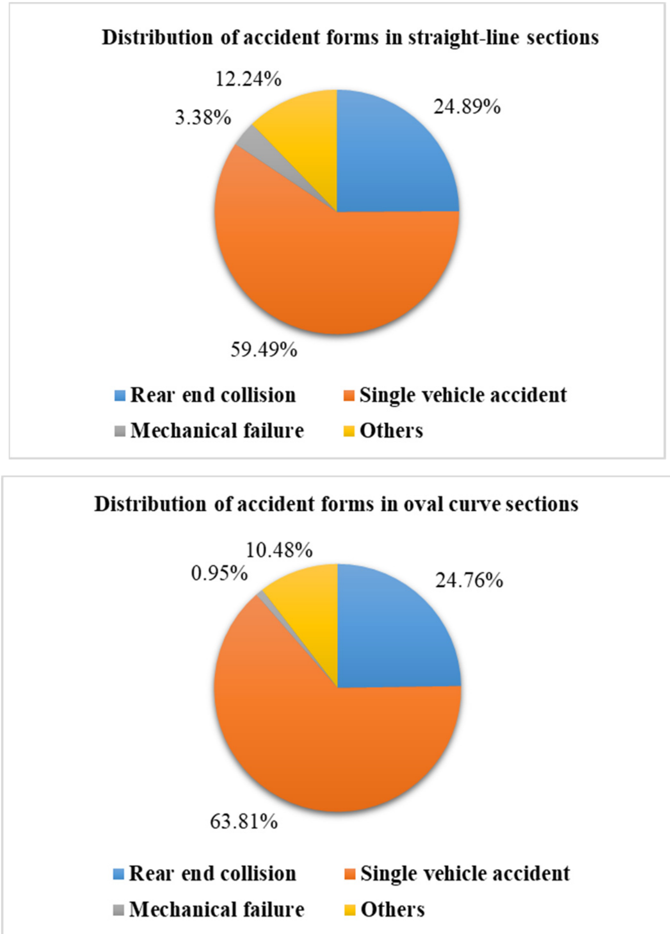


**Figure 4.** Distribution of accident forms in the compound curves section of Freeway.

From the above comparison, it can be seen that the main accident forms of the intermediate straight line section and the oval curve section are single vehicle accidents, accounting for more than half of the proportion of both. In the traffic accident account records, single vehicle accidents mainly show that the vehicle deviates from the center line of the traffic lane due to excessive speed or driver's misjudgment, resulting in rollover or impact on roadside guardrails and median guardrails.

### 3.2. Analysis of Traffic Safety in the Compound Curves Section

When selecting the influencing factors of traffic safety evaluation on the compound curves section, this paper focuses on selecting specific quantifiable data. The specific quantifiable indicators are analyzed from the geometric design indicators of two different types of curve sections. The selection basis and meaning of specific factors are described below.

According to the basic composition form of the compound curves, this paper specifies that the influencing factors of the straight-line section include the length of the first transition curve ($L_{S1}$), the radius ratio of adjacent circular curves ($U$), the length of the intermediate straight line ($L$) and the length of the second transition curve ($L_{S2}$). The influencing factors of oval curve sections include the length of the first transition curve ($L_{S1}$), the radius ratio of adjacent circular curves ($U$), the ratio of the parameter of the second transition curve to the radius of small circular curves ($A/R_2$) and the length of the third transition curve ($L_{S3}$). The specific meaning and calibration of influencing factors are shown in Figures 1 and 2.

### 3.3. Evaluation Index of Traffic Safety in the Compound Curves Section

In order to fully consider the traffic safety when passing through two kinds of compound curves, this paper studies the driving comfort and driving stability.

According to the relevant research of traffic psychology, the objective objects such as the road traffic environment will stimulate the driver to a certain extent, and different objects will also cause different degrees of stimulation due to their own differences. In 2009, Wu Huajin concluded that when the driver was overloaded by external stimuli, the driver would have a series of nervous physiological conditions such as excessive heart rate acceleration. Then, the driver's excessive tension would cause a series of wrong judgments and operations [20]. In 2018, Sugiono et al. used the relevant indexes of cardiac physiology in the safety evaluation of road alignment, and established a multiple regression model between the physiological indexes and the horizontal and vertical design parameters according to the relevant data such as the driver's electrocardiogram [21]. In 2007, Pan Xiaodong et al. studied that when the driver passes through the curve section at high speed, the physiological pressure of the heart was large and the heart rate changed greatly [22]. In conclusion, the traffic safety under corresponding conditions can be evaluated by studying the change of driver's heart rate during driving. In this paper, the mean value of heart rate change rate (recorded as $X$) is used as the evaluation index. The specific calculation method is as follows.

$$HRI_i = \frac{HR_{i+1} - HR_i}{HR_i} \times 100\% \tag{2}$$

$$X = \frac{1}{n}\sum_{i=1}^{n} HRI_i \tag{3}$$

where: $HRI_i$—heart rate growth rate during driver simulation (dimensionless); $HR_i$—heart rate of the driver at the $i$-th time (times/minute); $X$—average heart rate change growth rate within the study section (dimensionless); $n$—the number of calculation of the change rate of the heart rate within the scope of the study section (dimensionless).

In 2018, Song Cancan et al. used steering wheel angle high frequency energy ratio for driving load analysis [23], and in 2016, Liu Jun et al. used steering wheel angle for driving fatigue analysis [24]. For the evaluation of traffic safety, other vehicle external parameters such as yaw rate and lateral load offset rate are mainly used. In this paper, in order to directly reflect the driving stability of the driver when passing through two different compound curves, the mean value of steering wheel angle change rate recorded by the driving simulator platform is selected for traffic safety evaluation. This indicator can reflect the overall driving load of the driver in the process of passing through the compound curves section. The larger this indicator is, the more prone the vehicle is to traffic accidents. The mean value of steering wheel angle change rate (recorded as $Y$) is calculated as follows.

$$\theta I_i = \frac{\theta_{i+1} - \theta_i}{\theta_i} \times 100\% \tag{4}$$

$$Y = \frac{1}{n} \sum_{i=1}^{n} \theta I_i \tag{5}$$

where: $\theta I_i$—change rate of steering wheel angle at a certain time in the simulation process (dimensionless); $\theta_i$—the rotation amplitude of the steering wheel at the $i$-th moment in the simulation process (dimensionless); $Y$—the mean value of steering wheel angle change rate within the study section (dimensionless); $n$—number of steering wheel angle change rate calculations within the study section (dimensionless).

In order to compare the overall situation of vehicle lateral offset in the process of passing through two different compound curves, the average ratio of lateral offset change rate of driving track is used as the evaluation index (recorded as $Z$). By sorting out all the collected driving trajectory data, the change rate of the lateral deviation value of the driving trajectory in the study section at each time can be solved. The mean value of lateral offset change rate can evaluate from the two dimensions of lateral offset and longitudinal change of driving track. The specific calculation formula is as follows.

$$DI_i = \frac{D_{i+1} - D_i}{t_{i+1} - t_i} \times 100\% \tag{6}$$

$$Z = \frac{1}{n} \sum_{i=1}^{n} DI_i \tag{7}$$

where: $DI_i$—change rate of lateral offset in a certain period of simulation (m/s); $D_i$—lateral offset value of vehicle at time i during simulation (m); $Z$—mean change rate of lateral deviation value of driving track within the study section (dimensionless); $n$—number of calculation of lateral deviation change rate within the study section (dimensionless).

In order to synthesize the three evaluation indexes for traffic safety evaluation, this study proposes the comprehensive evaluation index $H$ to consider the three basic indexes, and the specific calculation formula is as follows.

$$H = \frac{1}{\sqrt{X^2 + Y^2 + Z^2}} \tag{8}$$

where: $H$—the comprehensive evaluation index; $X$—the mean value of the heart change rate; $Y$—the mean value of the steering wheel angle change rate; $Z$—the mean value of the lateral deviation offset change rate.

## 4. Virtual Reality Virtual Mapping Scheme

### *4.1. Establishment of Human–Computer Interaction Safety Experience Platform*

Based on the concept of virtual reality, this paper using multi-dimensional visual information modeling, VR, big data and human body monitoring technology, plans to adopt the virtual reality multi-dimensional mapping scheme and the human–computer interactive safety experience platform to conduct a systematic study on the traffic safety evaluation of the compound curves section. The data to be obtained include the driver's psychophysiological data, vehicle trajectory data and steering wheel angle data when passing through two kinds of compound curves. In 2012, Auberletjm et al. pointed out that the above method was the main development direction of relevant research [25].

The 3D visualization model of the same direction curve road section in this study is constructed using Openroads (Bentley, Exton, PA, USA), and the related road model and terrain information are imported using the secondary development platform (see Figure 5). During the driving simulation experiment, a driving simulator with UC win/Road is used. The platform can record the driving parameters when the driver passes the corresponding simulation road section, and can derive the corresponding real-time parameters according to the user's needs. The driving simulator adopts the platform developed (developed) by FORUM8 Co., Ltd., (Tokyo, Japan) which can simulate the cockpit of ordinary passenger cars to the greatest extent from the whole process of vehicle functions such as starting the engine, driving and stopping the engine. At the same time, based on the secondary development, this paper establishes the data channel between the software, and builds a multi-dimensional visual information model platform for the compound curves section.


**Figure 5.** Construction of road visualization model.

Then, based on the linear engineering modeling system, the virtual reality data model is described to form a clear structure, which provides the basis for the actual evaluation. Finally, the mapping mechanism and evolution process of the virtual reality model for the evaluation process of traffic safety in the compound curves section are clarified, as shown in Figure 6. The virtual reality model is described in the above way to provide data source and evaluation basis for constructing the safety evaluation model of the compound curves.

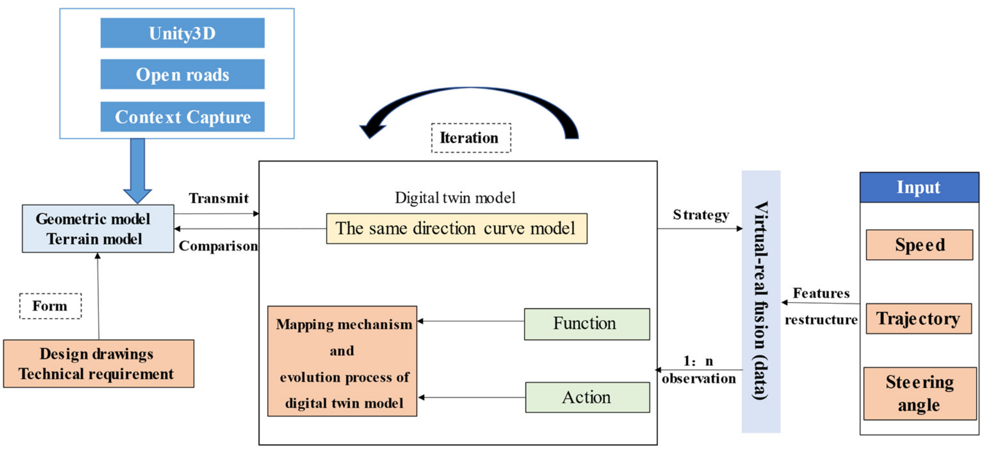


**Figure 6.** Virtual reality virtual mapping scheme of compound curves.

### *4.2. Orthogonal Experiment of Traffic Safety Evaluation*

When dividing the levels under different influencing factors, the specific values can be calibrated according to relevant technical specifications. The highway grade in this paper is freeway, so the level of influencing factors of orthogonal experiment of two compound curves sections can be specified in the following tables (Tables 4 and 5).

**Table 4.** Table of influence factors of straight-line section.

| Level | $L_{S1}$ (m) | $U$ | $L$ (m) | $L_{S2}$ (m) |
|---|---|---|---|---|
| 1 | 70 | 0.3 | 2V | 70 |
| 2 | 80 | 0.5 | 3V | 80 |
| 3 | 90 | 0.7 | 4V | 90 |
| 4 | 100 | 0.9 | 5V | 100 |

$U$ is the radius ratio of adjacent circular curves.

**Table 5.** Table of influencing factors of orthogonal experiment on oval curve section.

| Level | $L_{S1}$ (m) | $U$ | $A/R_2$ | $L_{S2}$ (m) |
|---|---|---|---|---|
| 1 | 70 | 0.2 | 0.6 | 70 |
| 2 | 80 | 0.4 | 0.7 | 80 |
| 3 | 90 | 0.6 | 0.8 | 90 |
| 4 | 100 | 0.8 | 0.9 | 100 |

For the convenience of research, this paper carries out significance analysis on the influencing factors of traffic safety in the compound curves section through the orthogonal experimental method. At the same time, the impact of interaction on the comprehensive evaluation index is not considered. According to the requirements of the orthogonal experiment table, it is necessary to collect the evaluation index data for 16 working conditions respectively arranged in the two compound curves sections.

The final results of this experiment are closely related to the selection of experimenters. The gender, education background, driving age, personality and physical health of experimenters will have a certain impact on the data collected from the experiment. In order to reduce the interference of irrelevant factors on the experiment as much as possible, 10 healthy people were selected as drivers after analysis. There are five male drivers and five female drivers. Through the research on drivers in the early stage, the educational background mainly includes bachelor's degree, master's degree and doctor's degree. The driving experience is mainly 3–5 years, so it can be considered that the experimenters have mastered the basic driving skills.

## 5. Evaluation and Analysis of Traffic Safety in the Compound Curves Section

### *5.1. Experimental Data Collection*

The driver's psychological data to be obtained in this paper are the change values of the heart rate with time in the driving process. The research process uses Acqknowledge5.0 software to automatically analyze the electrocardiogram after recording the data and produce the analysis results. The steering wheel angle data to be obtained in this paper are output by the driving simulation platform.

The distance to the left border (m) and the distance to the right border (m) can be obtained directly from the driving log file output by the human-computer interaction simulation platform. Meanwhile, the lateral offset ($D$) of the driving track is defined as the distance from the vehicle centerline to the road centerline. According to the composition of the road cross section, the lateral offset of the vehicle driving track is calculated by the following formula.

$$D = 6.375 - \left( A + \frac{11.25 - A - B}{2} \right) \tag{9}$$

where: $D$—Lateral deviation value of vehicle running track, m; $A$—distance from vehicle to left boundary, m; $B$—distance from the vehicle to the right boundary, m.

### *5.2. Analysis of Orthogonal Experiment Results*

In this paper, in order to make a comparative analysis of traffic safety in the compound curves section from the two aspects of driving comfort and driving stability, the three sub indicators are comprehensively considered. Therefore, after using the driving simulator and psychological instrument to complete the data collection of evaluation indicators, the average value of 10 groups of data under each working condition is calculated, and then the results are taken as the sub evaluation indicators under the corresponding working conditions. The experimental data collected in this paper are shown in the following table (Table 6).

**Table 6.** Table of experimental data and results.

| Num | The Mean Value of The Heart Change Rate ($X$) | | The Mean Value of The Steering Wheel Angle Change Rate ($Y$) | | The Mean Value of The Lateral Deviation Offset Change Rate ($Z$) | | Comprehensive Evaluation Index $H$ | |
|---|---|---|---|---|---|---|---|---|
| | Straight-Line | Oval Curve | Straight-Line | Oval Curve | Straight-Line | Oval Curve | Straight-Line | Oval Curve |
| 1 | 0.1680 | 0.0247 | 0.0855 | 0.0291 | 0.0438 | 0.1527 | 5.1669 | 6.3521 |
| 2 | 0.2163 | 0.0257 | 0.0790 | 0.0219 | 0.0395 | 0.1908 | 4.2799 | 5.1600 |
| 3 | 0.2469 | 0.0249 | 0.0823 | 0.0225 | 0.0431 | 0.2017 | 3.7910 | 4.8908 |
| 4 | 0.1917 | 0.0289 | 0.0874 | 0.0188 | 0.0436 | 0.2539 | 4.6485 | 3.9023 |
| 5 | 0.1980 | 0.0225 | 0.0827 | 0.0260 | 0.0300 | 0.1530 | 4.6146 | 6.3775 |
| 6 | 0.2123 | 0.0267 | 0.0875 | 0.0279 | 0.0318 | 0.1759 | 4.3141 | 5.5518 |
| 7 | 0.1938 | 0.0398 | 0.1041 | 0.0264 | 0.0326 | 0.1861 | 4.4973 | 5.2052 |
| 8 | 0.2163 | 0.0237 | 0.0995 | 0.0243 | 0.0368 | 0.2646 | 4.1511 | 3.7481 |
| 9 | 0.1676 | 0.0294 | 0.1214 | 0.0380 | 0.0335 | 0.2128 | 4.7706 | 4.5833 |
| 10 | 0.2060 | 0.0140 | 0.1295 | 0.0575 | 0.0458 | 0.2133 | 4.0380 | 4.5164 |
| 11 | 0.2392 | 0.0230 | 0.0664 | 0.0480 | 0.0411 | 0.2208 | 3.9741 | 4.4022 |
| 12 | 0.1978 | 0.0289 | 0.0930 | 0.0346 | 0.0416 | 0.2402 | 4.4949 | 4.0909 |
| 13 | 0.1827 | 0.0215 | 0.0926 | 0.0729 | 0.0492 | 0.1601 | 4.7461 | 5.6433 |
| 14 | 0.1738 | 0.0196 | 0.1004 | 0.0442 | 0.0345 | 0.1613 | 4.9116 | 5.9378 |
| 15 | 0.1939 | 0.0270 | 0.0968 | 0.0572 | 0.0316 | 0.1685 | 4.5658 | 5.5563 |
| 16 | 0.2328 | 0.0344 | 0.0878 | 0.0547 | 0.0431 | 0.1487 | 3.9600 | 6.1689 |

After the driving simulation is carried out according to the requirements of orthogonal experiment, the variance results and range results of the experimental data of the two compound curves sections are analyzed by SPSS. The analysis results are shown in the following tables (Tables 7 and 8).

**Table 7.** Analysis of variance results of straight section.

| Error Source | Sum of Squared Deviations | Freedom | F | Significant Level |
|---|---|---|---|---|
| Factor 1 $L_{S1}$ | 0.115 | 3 | 1.502 | NO |
| Factor 2 $U$ | 0.883 | 3 | 11.586 | YES |
| Factor 3 $L$ | 0 | 0 | 0 | NO |
| Factor 4 $L_{S2}$ | 1.054 | 3 | 13.824 | YES |
| Error | 0.152 | 6 | | |
| Sum | 316.599 | 15 | | |

**Table 8.** Analysis of variance results of oval curve sections.

| Error Source | Sum of Squared Deviations | Freedom | F | Significant Level |
|---|---|---|---|---|
| Factor 1 $L_{S1}$ | 1.921 | 3 | 12.698 | YES |
| Factor 2 $U$ | 3.345 | 3 | 22.113 | YES |
| Factor 3 $A/R_2$ | 4.127 | 3 | 27.285 | YES |
| Factor 4 $L_{S3}$ | 1.626 | 3 | 10.748 | YES |
| Error | 0.151 | 3 | | |
| Sum | 432.313 | 15 | | |

From the results of variance analysis, it can be seen that under experiment conditions, the radius ratio of adjacent circular curves and the length of the transition curve of the second circular curve have a significant impact on the comprehensive indicators for the intermediate straight line section. For the oval curve, the length of the first transition curve, the radius ratio of adjacent circular curves, the ratio of the second transition curve parameters to the radius of circular curves and the length of the third transition curve all have a significant impact on the comprehensive indicators.

In the straight section, it can be judged that the influence degree of the four influencing factors on the comprehensive evaluation index is $L_{S2} > U > L_{S1} > L$. According to $F_{0\cdot05}$ (3,3) = 9.28, the impact of the length of the clamping line on the comprehensive evaluation index is almost zero. In 2001, Sun Xianli concluded the same results [26]. The main reason is that the length of the intermediate straight line between the compound curves is too short, which will cause the driver's illusion of reverse bending. Through relevant research, it can be concluded that in the actual driving process, when the driver is aware of the change or adverse driving conditions ahead, the reaction time is only 1.5 s, and then the braking time such as braking is only 1.0 s, that is to say, it only takes 2.5 s for the driver to stop passively due to the form ahead. In this paper, the minimum level of the length of the clamping line between the identical circular curves is specified as double that of the the design degree. After analysis, the driving demand of the driver can be met at this level. Therefore, after the orthogonal experimental analysis of the impact speed of the length of the clamping line, it is found that the impact of the length of the clamping line on the comprehensive evaluation index is almost zero.

In the oval curve section, the influence degree of the four influencing factors on the comprehensive evaluation index can be judged as $A/R_2 > B > L_{S3} > L_{S1}$. The ratio of the second transition curve parameters to the radius has the greatest impact on the comprehensive evaluation index, followed by the ratio of the radius of adjacent circular curves. This is because in the oval curve, the transition between the two circular curves depends on a transition curve with gradual curvature, and the length of the transition curve is significantly shorter than that of the intermediate straight line in the intermediate straight line section. Moreover, under each working condition in this paper, the second circular curve adopts the limit radius, which leads to the sudden adverse situation of the road alignment when the driver enters the second circular curve from the first circular curve. At this time, the driver will increase the vehicle's lateral offset trajectory due to the untimely adjustment of the steering wheel or deceleration. In 2019, Fu Xinsha arrived at the same results [27]. At the same time, the third transition curve is the transition line before connecting the second circular curve and the intermediate straight line. In 2011, Lin Yu et al. showed that when the driver drove out from a limit working condition, the driver was still in a relatively nervous state. If the length of the transition curve is insufficient, the driver will make mistakes in operation [28].

From the range analysis results (see Table 9), it can be seen that the radius ratio of adjacent circular curves and the length of the second transition curve have a great impact on the comprehensive evaluation index for the straight-line section. For the oval curve, the radius ratio of adjacent circular curve and the radius ratio of the second transition curve to circular curve have a great impact on the comprehensive evaluation index. In addition, according to the K value, the relationship between the influencing factors and the comprehensive evaluation indicators under the two compound curves sections can be obtained. Finally, the correlation between the comprehensive evaluation indicators and the influencing factors can be established by using the data regression analysis software based on the mean value of the influencing factors at different levels (Figures 7–9).

**Table 9.** Range analysis results of curve sections in the same direction.

| | Straight-Line | | | | Oval Curve | | | |
|---|---|---|---|---|---|---|---|---|
| **Parameter** | $L_{S1}$ | $U$ | $L$ | $L_{S2}$ | $L_{S1}$ | $U$ | $A/R_2$ | $L_{S3}$ |
| K1 | 17.89 | 19.3 | 17.42 | 19.07 | 22.48 | 22.96 | 20.31 | 21.59 |
| K2 | 17.58 | 17.54 | 17.96 | 17.15 | 21.18 | 21.17 | 20.88 | 18.95 |
| K3 | 17.28 | 17.25 | 17.62 | 16.4 | 19.16 | 20.05 | 17.59 | 21.95 |
| K4 | 18.18 | 16.83 | 17.93 | 18.3 | 19.27 | 17.91 | 23.31 | 19.59 |
| k1 | 4.47 | 4.82 | 4.35 | 4.77 | 5.62 | 5.74 | 5.08 | 5.4 |
| k2 | 4.39 | 4.39 | 4.49 | 4.29 | 5.3 | 5.29 | 5.22 | 4.74 |
| k3 | 4.32 | 4.31 | 4.41 | 4.1 | 4.79 | 5.01 | 4.4 | 5.49 |
| k4 | 4.55 | 4.21 | 4.48 | 4.57 | 4.82 | 4.48 | 5.83 | 4.9 |
| Range R | 0.23 | 0.62 | 0.14 | 0.67 | 0.83 | 1.26 | 1.43 | 0.75 |

where: *Ki*—Sum of H values of parameters corresponding to this column at level i; *ki*—The average value of *H* of the parameter corresponding to this column at level *i*; *H*—the comprehensive evaluation index.

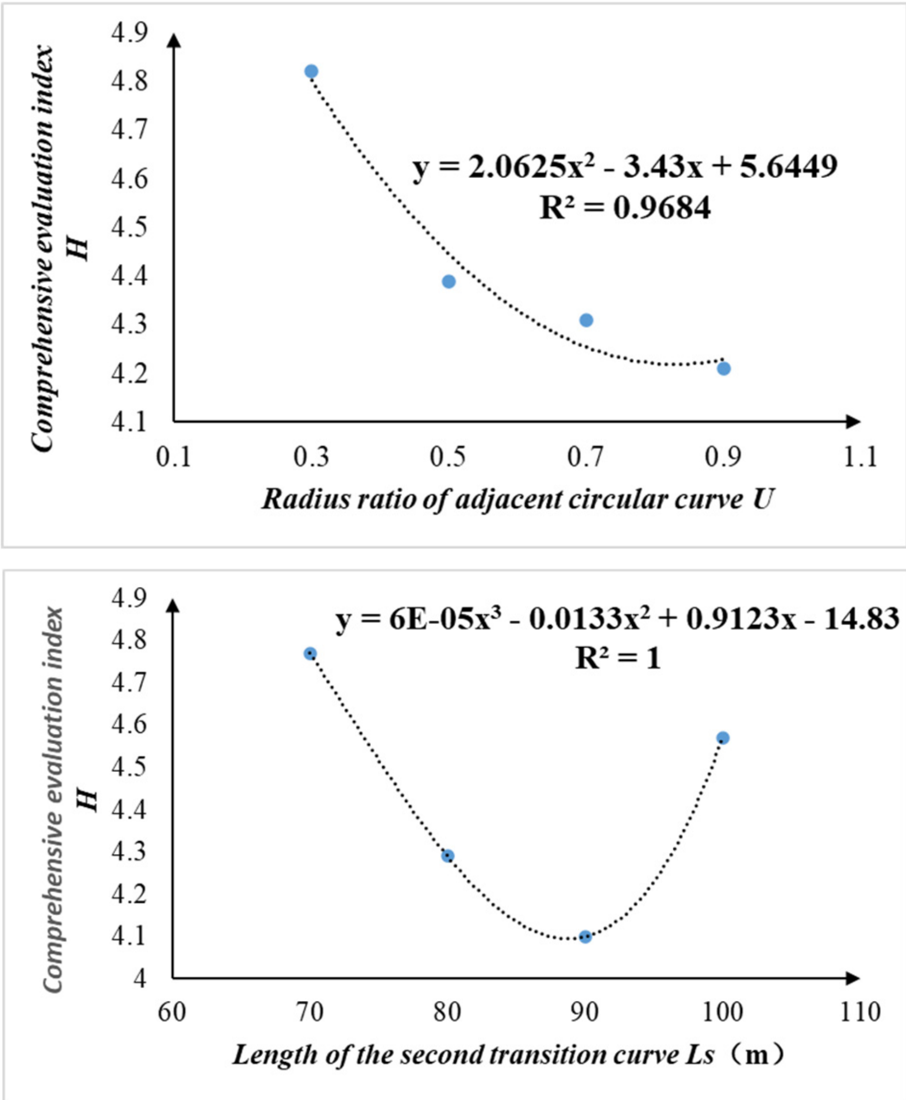


**Figure 7.** Variation law of $H$ with $U$ and $L_{S2}$ in straight section.

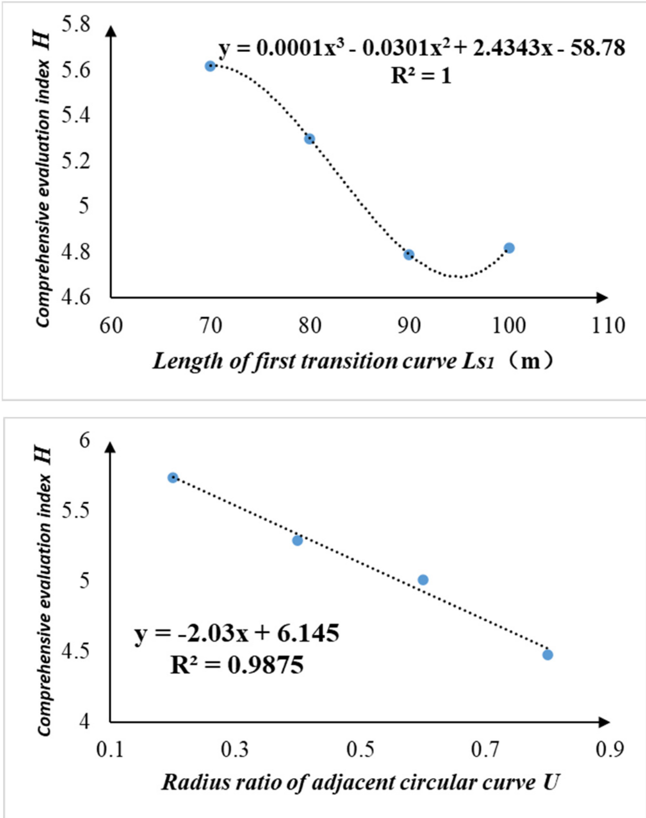


**Figure 8.** Variation law of $H$ with $L_{S1}$ and $U$ in oval curve section.

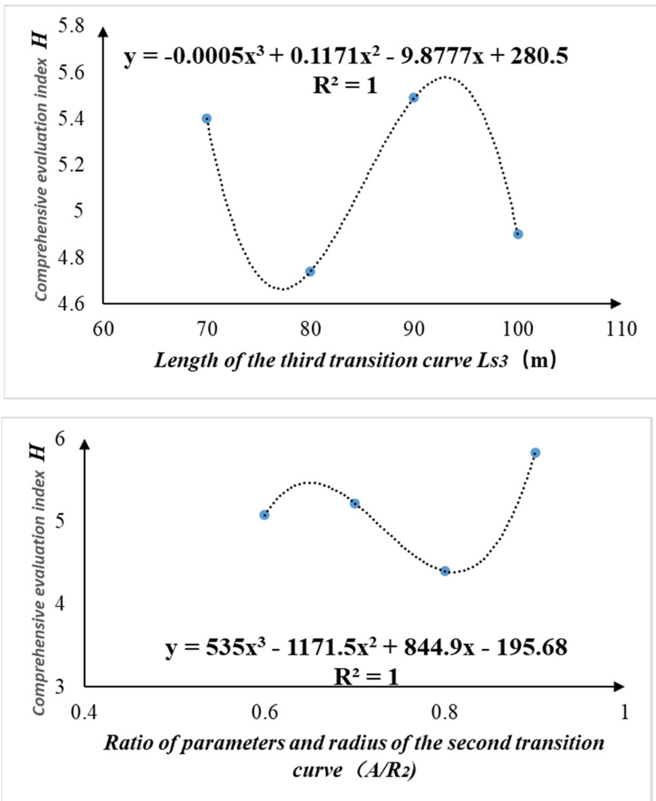


**Figure 9.** Variation law of $H$ with $A/R_2$ and $L_{S3}$ in oval curve section.

The correlation between the comprehensive evaluation index of traffic safety and the influencing factors can be obtained through the range analysis results, which provides the basis for the subsequent establishment of traffic safety evaluation model.

### *5.3. Evaluation Model of Traffic Safety in the Compound Curves Section*

After clarifying the influencing factors of the traffic safety of the two compound curves sections, the corresponding traffic safety evaluation models are established for the intermediate straight line section and the oval curve section respectively. In this paper, when establishing the traffic safety evaluation model for two kinds of compound curves sections, combined with the global optimization algorithm in the professional nonlinear analysis software 1stOpt, the regression coefficient and function form of each function are determined without considering the initial value problem. The analysis software 1stOpt used in the study can select the optimal model according to the Levenberg–Marquardt method and the general global optimization method after reading the data. The traffic safety evaluation models of the two compound curves sections are as follows (see Table 10).

**Table 10.** Evaluation model of traffic safety in the compound curves section.

| Type | Traffic Safety Evaluation Model | Correlation Coefficient |
|---|---|---|
| straight-line section | $H_1 = -23.58 - 4.945x_1 + 3.408{x_1}^2 - 0.413x_2 + 0.0024{x_2}^2$ | 0.87 |
| oval curve section | $H_2 = -58.691 + 10.982x_3 - 0.1335{x_3}^2 + 0.0005{x_3}^3 - 2.0311x_4 + 183.074x_5 - 259.981{x_5}^2 + 119.429{x_5}^3 - 9.869x_6 + 0.117{x_6}^2 - 0.00046{x_6}^3$ | 0.98 |

where: $x_1$⁻$L_{s2}$; $x_1$⁻$U$; $x_3$⁻$L_{s1}$; $x_4$⁻$U$; $x_5$⁻$A/R_2$; $x_6$⁻$L_{s3}$.

## 6. Evaluation Method of Traffic Safety in the Compound Curves Section

### *6.1. Classification of Traffic Safety*

Through the statistical analysis of all simulation data, the comprehensive evaluation indexes of traffic safety are divided according to a certain interval, and the cumulative frequency distribution curves of the comprehensive evaluation indexes of the two compound curves sections can be obtained respectively (see Figures 10 and 11 and Table 11).

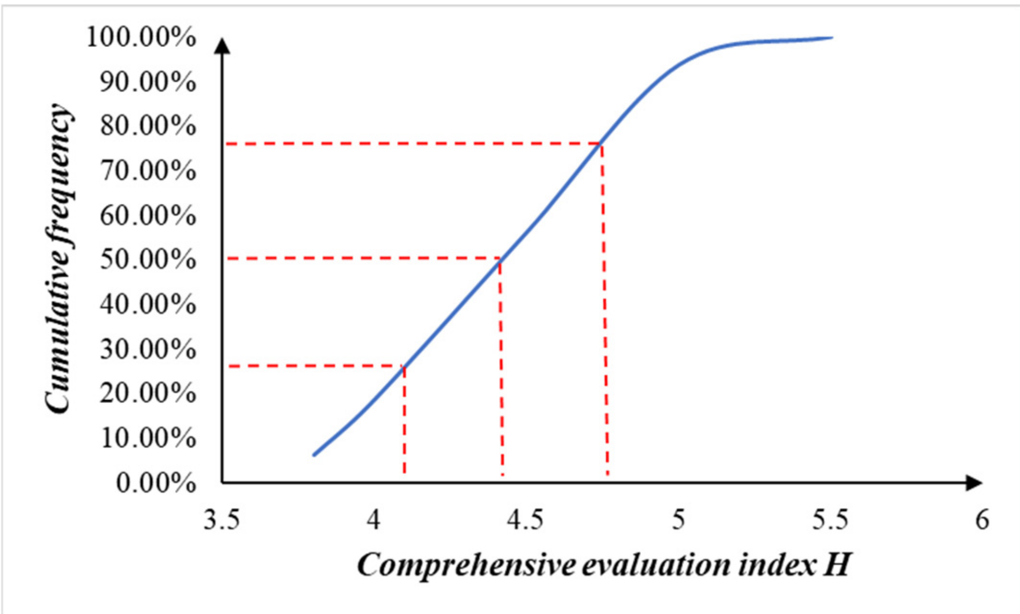


**Figure 10.** Cumulative frequency distribution of H in straight-line section.

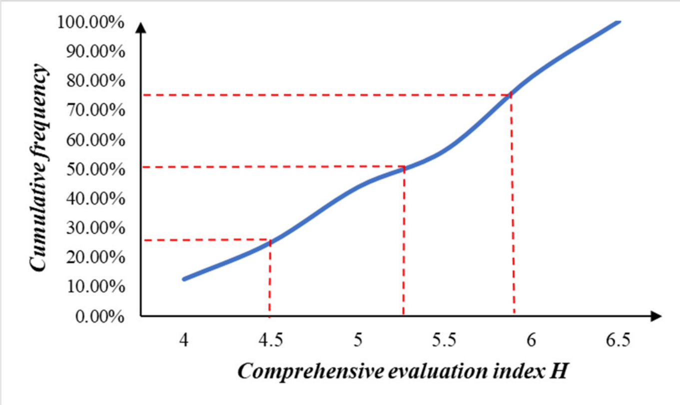


**Figure 11.** Cumulative frequency distribution of H in oval curve section.

**Table 11.** Classification of traffic safety.

| Type | Safe | Less Safe | Less Dangerous | Dangerous |
|---|---|---|---|---|
| straight-line section | >4.78 | $4.46 < H < 4.78$ | $4.23 < H < 4.46$ | <4.23 |
| oval curve section | >5.86 | $5.32 < H < 5.86$ | $4.59 < H < 5.32$ | <4.53 |

In this paper, the greater the driving risk, the smaller the comprehensive evaluation index. Therefore, according to the principle of statistics, 25%, 50% and 75% of the comprehensive evaluation indexes of the two compound curves are used as the division threshold, and the traffic safety level is divided into four levels: safe, less safe, less dangerous and dangerous.

### *6.2. Engineering Application Cases*

In order to obtain the numerical change of the comprehensive evaluation index of traffic safety when the radius of the second circular curve of the compound curves changes, it is only necessary to change the radius of the second circular curve according to a certain step during the experimental design to set up a digital model. After the digital model is established, the evaluation data can be collected according to the experimental steps mentioned above. The comparison between the driving simulation calculation results and the safety evaluation model calculation results of the two compound curves sections under different second circle curve radius is as follows (Table 12).

**Table 12.** Value of comprehensive evaluation index under different working conditions.

| $R_2$ | Intermediate Straight Line | | Oval Curve | |
|---|---|---|---|---|
| | Simulation Fitting Value | Model Calculation Value | Simulation Fitting Value | Model Calculation Value |
| 400 | 5.000 | 5.001 | 6.270 | 6.272 |
| 500 | 4.280 | 4.281 | 6.055 | 6.053 |
| 600 | 4.110 | 4.112 | 6.342 | 6.348 |
| 700 | 4.622 | 4.641 | 5.410 | 5.412 |
| 800 | 4.361 | 4.127 | 4.853 | 4.641 |
| 900 | 4.365 | 4.162 | 6.835 | 6.536 |

From the calculation results, it can be seen that when the radius of the second circular curve is less than 700 m, the comprehensive evaluation index obtained from the driving simulation calculation is close to the calculation result of the traffic safety evaluation model. Therefore, it can be considered that the traffic safety evaluation model proposed in this study can evaluate the extreme working conditions with the radius of the second circular curve less than 700 m.

This paper is based on the safety evaluation data of the ZX project. By sorting out the design background data and route data of the project, it can be known that ZX freeway has a total length of 88.548 km, a design speed of 80 km/h, and is constructed according to the standard of two-way four lane freeway, with a subgrade width of 25.5 m. Through checking the preliminary design data of the project, there are five intermediate straight lines and seven oval curve sections within the evaluation section of ZX project. Moreover, the intermediate straight line do not meet the 6V length requirements under the control of operation speed and design speed. Among them, three sections are located in the tunnel section, where the driver's line of sight is blocked, so it is not easy to have the illusion of reverse bending. The rest are located in the bridge section, which is easy to have the illusion of reverse bending. It is suggested to adjust the horizontal alignment design in the next stage to meet the specification requirements. When conditions are limited, add sight guidance signs and strengthen speed control for sections that do not meet the requirements of running speed, so as to reduce driving risk. The design indexes of the oval curves meet the specification requirements.

In order to further verify the traffic safety of the compound curves section in this project, this paper carries out the traffic safety evaluation for the compound curves section with the radius of the second circular curve less than 700 m. According to the comprehensive evaluation index model of traffic safety, when the vehicle passes at the speed of 80 km/h, the calculation results of comprehensive evaluation indexes of traffic safety of two short intermediate straight line sections and oval curve sections are shown in the table below (Table 13).

**Table 13.** Safety inspection under extreme working conditions.

| Road Type | Comprehensive Evaluation Index | Safety Level |
|---|---|---|
| Straight-line Section 1 | 4.537 | Less safe |
| Straight-line Section 2 | 4.059 | Dangerous |
| Oval curve 5 | 6.332 | Safe |

According to the above calculation results, the safety level of the second short straight section is dangerous. Therefore, for the second straight-line section, although the design indicators meet the general requirements of the specification, the combination of plane indicators has a great impact on traffic safety. In order to improve the road safety level, the short straight-line section can be limited in advance to reduce the driver's speed to a certain level in advance, so as to ensure the safe passage of the short straight-line section in the project. According to the setting principle of anti-collision guardrails in the multi center elliptic curve section of freeway, guardrails are set in this section, and the protection grade of guardrails is sb. In order to further improve the anti-collision level, guardrail transition sections can be set in front of and behind the road section according to the specifications, and the guardrail level can be improved in the road section.

## 7. Discussion and Conclusions

In this paper, two commonly used sections of the compound curves in the freeway are taken as the research object. Based on the concept of VR, driving simulation experiments are carried out in the built human–computer interaction platform respectively, and the comprehensive evaluation indicators of traffic safety are fit according to the platform output data, so as to establish the regression model of traffic safety evaluation of the two kinds of compound curves, and finally divide the thresholds of different levels according to the comprehensive evaluation indicators of traffic safety. This traffic safety evaluation method comprehensively considers the overall impact of driver, vehicle, road and environment, enriching the traffic safety evaluation index system.

When the driver passes through the oval curve section, the overall heart rate level is higher than that of the straight-line section. In addition, when the driver passes the second curve of the two compound curves, the change of heart rate in the straight-line section is more obvious, and the change range can be increased by about 15–20%, while that in the oval curve section is increased by about 5%. There are three obvious changes in the steering wheel angle in the straight section, which are right deviation at the midpoint of the two continuous circular curves in the same direction and at the slow straight point of the second circular curve. The maximum steering wheel angle occurs within the range of the second circular curve section. There are four obvious changes in steering wheel angle in oval curve section, which are at the midpoint of two circular curves, the transition curve and the straight point within the range of the second circular curve. The maximum steering wheel angle occurs in the transition curve between two circular curves. The change law of the lateral offset of the two compound curves sections under different design speeds shows a roughly consistent trend, showing the change law of "right deviation-left deviation-right deviation-left deviation" in the process of driving forward.

The traffic safety evaluation model can be applied to the compound curves sections with the radius of the second circular curve less than 700 m. The traffic safety evaluation model under other working conditions needs to be reestablished through experiments.

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