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Research on Geometric Design Standards for Freeways under a Fully Autonomous Driving Environment

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Abstract: The formulation of the current geometric design standard for freeways considers the influence of the "human-vehicles-road-environment" system. In the fully autonomous environment, the driver has been liberated from the system, which means that the influence of "human" will be reduced. The requirements or limitations of the freeway geometric design standard, which consider the driver's psychological and physical factors in the traditional driving environment, can be more flexible in the fully automatic driving environment. By using the methods of comparative analysis, theoretical analysis, and theoretical calculation, this article researches the geometric design standard for freeways in an autonomous driving environment from four aspects: control elements of geometric design, horizontal alignment, vertical alignment, and cross-section elements. The main contribution of this article is to propose the recommended values of the geometric design standard for freeways in a fully autonomous driving environment, which can provide reference for the formulation of relevant standards or specifications for autonomous driving roads in the future.

Keywords: freeway; full automation vehicles; geometric design standards; sight distance

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1. Introduction

As one of the new products of Internet-of-vehicles technology, autonomous driving technology has gradually developed from a low level to a high level, from simple to complex. Autonomous driving technology has achieved rapid progress and development with the support of 5G, high-precision satellite positioning and navigation systems, the Internet of vehicles, and sensor systems. The traditional "human-vehicles-road-environment" transportation system will transform into the "Internet-vehicles-road-environment" transportation system, as shown in Figure 1.

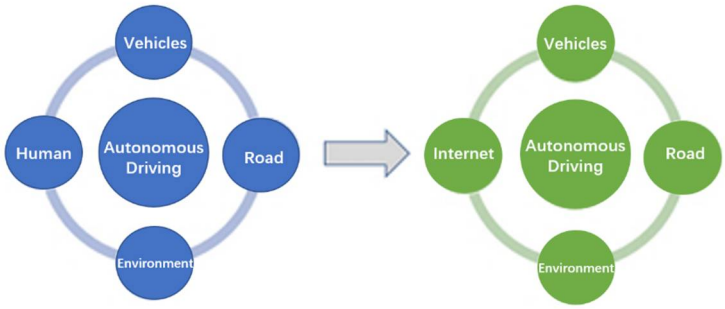

Figure 1. Transformation of the transportation system.

According to related studies [1,2] and the standards of the Society of Automotive Engineers (SAE), autonomous driving technology is generally divided into six levels: L0, No Driving Automation (NA); L1, Driver Assistance (DA); L2, Partial Driving Automation (PA); L3, Conditional Driving Automation (CA); L4, High Driving Automation (HA);

L5, Full Driving Automation (FA). Up to now, most countries have reached L3 (CA), a few developed countries have reached L4 (HA), and L5 (FA) is just around the corner. This article studies the geometric design standard for freeways in L5. The autonomous driving technology below refers to L5, that is, autonomous driving technology without the participation of the driver.

In the traditional artificial driving environment, the perception and interaction of traffic information are mainly realized by drivers. Drivers perceive and receive information through their eyes (vision), ears (hearing), and their own driving experience. However, due to the negligence of the driver, the untimely perception of information, and the poor performance of information perception, traffic accidents often occur. In the traditional artificial driving environment, many characteristics of traffic information are closely related to the characteristics of drivers. Studies have shown [3] that the driver's sight distance and field of view are relatively limited, and the information he/she perceives is relatively singular. For example, in the process of high-speed driving, the driver cannot collect the driving-state information of the front and rear vehicles while perceiving the information of the signs and markings. The physiological and psychological characteristics of drivers have great limitations. The driver's understanding of the motion information of the vehicle ahead (speed, following distance, etc.) and road environment information (guidance information, warning information, prohibition information, etc.) is prone to deviations, and as a result, the accuracy and precision of the information are reduced. In addition, the human brain needs a longer reaction time when encountering emergencies. The driver's reaction time is mainly controlled by factors such as age, gender, psychological and physiological conditions, driving experience, and driving skill proficiency. It is difficult to ensure the timeliness and uniformity of information processing by drivers. For this reason, countries often need to take into account the needs of low-level drivers when designing geometric standards. As a result, the value of the specification is relatively conservative, and it is a great waste of engineering construction and land resources.

In a fully autonomous driving (L5) environment, the on-board sensors of autonomous vehicles act as the driver's sensory organs, thereby sensing the driving status of surrounding vehicles and road traffic environment information. The vehicle's central processing system acts as a human brain. It analyzes, fuses, and processes the information perceived by the sensor and finally gives out instructions to control the vehicle's operation. In addition, the roadside monitoring system will also collect the road traffic flow, road conditions, and road alignment information back to vehicles in time [4,5] to improve road safety and driving efficiency. In this process, the vehicles are not isolated from each other. With the help of the Internet of vehicles [6], autonomous vehicles use an in-vehicle intelligent system to monitor the driving conditions and surrounding traffic environment information in real time and share this information with other vehicles in a timely manner. The ability of information acquisition and decision making of an autonomous vehicle is much better than that of a traditional driver. Autonomous vehicles can quickly perceive and recognize obstacles, which takes much less time than the driver, and the perception results are more accurate. The central processing system quickly analyzes and calculates the obstacle information and vehicle's driving state information and then sends a braking command to the vehicle's control center to achieve emergency avoidance. Therefore, the reaction time of autonomous vehicles must be shorter than traditional drivers, and the braking success rate is higher. With the support of Internet-of-vehicles technology and high-precision satellites, through the interaction and transmission of information, autonomous vehicles can predict their driving environment and driving route in advance [7]. As a result, under the premise of no emergencies, vehicles can drive smoothly and safely on straight lines or curves with suitable angle, speed, and acceleration. When driving on a curve, the uniformly changing acceleration of autonomous vehicles can reduce the impact of the lateral motion of the vehicle and improve the driving stability and passenger comfort [8].

To sum up, in a fully autonomous driving environment, the vehicle is no longer controlled by the driver, and human factors no longer affect traffic safety. Vehicle operation

does not need to consider the driver's psychological and physical characteristics, but passenger comfort at high speed still needs to be considered. Therefore, in a fully autonomous driving environment, autonomous vehicles have different requirements for the geometric design standards of highways. The current road design standards in various countries are not fully applicable to autonomous driving. Existing freeway transport standards and infrastructures need to be retrofitted to match new requirements and create an adaptive, comfortable, and economical operating environment for autonomous vehicles.

It will be a while before fully autonomous driving technology is successfully achieved. There will be a transition period between the human driving phase and the autonomous driving phase. At present, the geometric design of freeways in China still adopts the road design standards and specifications under the manual driving environment. However, many scholars have begun to explore and study how to build an intelligent freeway that can support unmanned driving in the future. This article will study the design criteria of freeways in a fully autonomous driving environment from the perspective of safety and economy and further supplement and improve the research in this field. The research results of this paper will provide technical reference for the construction of intelligent freeways. It will enable designers to take into account the needs of autonomous vehicles for roads in road planning and design, reduce the cost of traditional road reconstruction, and control the cost of construction (reconstruction). At the same time, the research results of this article will also optimize and guide the design of freeways in the fully autonomous driving environment, so that the future construction of freeways will be more suitable for the operating characteristics of vehicles and social and economic conditions.

2. Literature Review

Many scholars conduct research on autonomous driving technology through different methods. These studies mainly focus on the perception and recognition process of sensors, the control system of vehicles, the obstacle avoidance system of vehicles, the traffic flow characteristics of human–machine hybrid driving, and the advantages of the Internet of vehicles. There is no systematic research on the road design standards for autonomous vehicles. Zhu H [9] summed up the advantages and disadvantages of sensors by analyzing the research status of sensor environment perception and modeling technology. Then, he proposed the latest algorithms and modeling methods for lane line recognition, obstacle perception, traffic sign recognition, behavior analysis, vehicle following, road environment cognition, etc. Welde Y et al. [10] believe that existing infrastructure design and operation standards were developed to meet the needs of human drivers, which may not be the best choice for autonomous vehicles (AVs). Based on the perception reaction time of the autonomous vehicle system, they used the modified parameters to recalculate the parking sight distance and vertical curve length requirements of level three and level five autonomous vehicles. They then compared current U.S. design standards with the indicator values suggested in the research, which showed that road design in an autonomous driving environment is more economical. Yoo H et al [11] proposed a gradient-boosting transformation method to generate new grayscale images from RGB color images. On this basis, they developed a novel algorithm for lane detection and recognition, which improved the performance of the lane detection system. Based on the traffic data provided by the Auckland Highway and NZ Transport Agency (NZTA), Li D [12] and others comprehensively evaluated the impact of different autonomous vehicle mixing rates on the mobility, safety, driving behavior, emissions, and fuel consumption of highways. Liu J et al. [13] proposed a multi-sensor integrated intersection cooperative collision avoidance method based on a GPS/DR structure. It obtains an intersection collision resolution strategy through the fusion and calculation results of various information collected by sensors, the lane-level road sign database, and the designed four-stage logical frame structure, so as to effectively resolve vehicle conflicts and ensure intersection traffic safety. Olia A et al. [14] developed a micro-simulation traffic-modeling framework to model the interaction between vehicles and infrastructure. This model can assess the potential impact of connected vehicles on

mobility, safety, and the environment in infrequent congestion situations. The results of the study show that connected vehicles can alleviate congestion, reduce travel time, reduce emissions, and improve driving safety. Jiménez F et al. [15] proposed a new automatic collision avoidance system based on the information provided by a laser scanner sensor. The system uses detailed digital map information to assess the surrounding safe area, and in case of danger, the vehicle can take the most appropriate response (emergency braking or lane change) to avoid the hazard. Kandarpa [16] believes that in a traditional artificial driving environment, road design standards and guidelines are formulated according to the needs of drivers and traffic characteristics. This may not be the best choice in an autonomous driving environment. However, he did not conduct research on road design standards in an autonomous driving environment. Rahman Md Hasibur [17] and others believe that connected autonomous vehicles (CAV) are expected to improve traffic safety and driving efficiency by reducing driving errors that often occur in humans. By comparing the safety and mobility of different CAV technologies (i.e., connected automated vehicles (CAV), autonomous vehicles (AV), and connected vehicle (CV)), it is concluded that the driving behavior of CAV is safer than AV. In addition, the results of this study show that by implementing the multi-vehicle communication system's CAV in the highway section, the traffic efficiency and safety of the road are significantly improved.

Chinese scholars' research on autonomous driving technology in an autonomous driving environment mainly focuses on the application of the Internet of vehicles, visual perception technology and sensor technology of autonomous vehicles, safe distance models, and matching of autonomous vehicles with current road standards, sexual analysis, and thinking. Baihua L [18] and others designed a control system for autonomous obstacle avoidance for autonomous vehicles. The system monitors and detects real-time traffic conditions in the adjacent lanes of autonomous vehicles through sensor technology and image processing technology. At the same time, according to the road conditions in front of the vehicle, the system can automatically change lanes safely and smoothly during vehicle operation. Changyin D [19] simulated and analyzed a scene of an autonomous vehicle leaving the main line according to the car-following characteristics and lane-changing model of the autonomous vehicle. On this basis, he proposed a path control strategy for autonomous vehicles to exit the main line and enter the exit ramp. Moreover, he optimized the control strategy and established a related evaluation model through the designed simulation experiments. Chao C [20] reduced the interference of other road marking information on the lane line recognition effect by performing grayscale processing, noise reduction processing, and separation on the image information collected by the video collector. Then, he extracted the lane line feature points and calculated the position of the lane's center line. Finally, he obtained the centerline of the lane by fitting these feature points and proposed a method that can combine the real-time position information of the vehicle to realize the lane departure warning of the autonomous vehicle. Xiaoming H et al. [21] studied the braking performance of autonomous vehicles on straight road sections and curved road sections through CarSim/Simulink simulation experiments based on the braking principle of autonomous vehicles, the texture characteristics of asphalt pavement, and the braking model of the vehicle. Based on the research results, they proposed the braking distance requirements of autonomous vehicles at different design speeds.

Most of the current research focuses on the development of connected autonomous vehicles in a fully autonomous driving environment, road environment recognition, the mechanism of autonomous vehicles overtaking, the modeling and simulation of mixed human–machine driving traffic flow, and autonomous driving laws and regulations, etc. There is little research on road technical indicators in an autonomous driving environment, which mainly focuses on the vertical curve length and the stopping sight distance. Few scholars have considered the applicability of traditional road design standards and autonomous driving traffic characteristics. In addition, few scholars have explored and systematically studied the design standards and technical indicators of freeways in a fully autonomous driving environment.

3. Elements of Design

This section studies the applicability of the main control factors in geometric design criteria in a fully autonomous driving environment. By means of comparative analysis and theoretical analysis, this section analyzes the applicability of designing speed, designing vehicles, and identifying line of sight in a fully autonomous driving environment. Then, we propose the recommended value of stopping-sight distance by means of braking model research and theoretical calculation.

3.1. Design Speed

Many technical indicators of freeways are related to the design speed. They should be matched and coordinated with the design speed. In a fully autonomous driving environment, factors that restrict the driving of autonomous vehicles will be reduced, and freeway infrastructure conditions will become better and better, so the speed of autonomous vehicles will be further increased. The design speed of freeways will exceed 120km/h in the future [22].

Therefore, in order to better adapt to the intelligent development of transportation infrastructure, this study extends the design speed on the basis of the traditional freeway design standards, based on a fully autonomous driving environment, transportation technology, and consideration of freeway function, and increases the design speed to 180km/h. According to related research [23], the design speed of freeways in an autonomous driving environment is divided into four levels, as shown in Table 1.

Table 1. Freeway classification based on automatic driving technology.

Level	Level 3 Freeway			Level 2 Freeway			Level 1 Freeway			Normal Freeway		
Design speed (km/h)	180	160	140	160	140	120	140	120	100	120	100	80

3.2. Design Vehicles

The dimensions, weight, and running characteristics of the designed vehicle are all important references for freeway geometric design. After researching domestic and foreign autonomous driving technology and autonomous driving vehicles (ADV) [24,25], we found that major car companies have not changed vehicle exteriors and dimensions. They all choose to load various cameras, lidar sensors, laser rangefinders, and central processing units (CPU) on traditional vehicles to achieve autonomous driving. Although ADVs generally choose to put lidar on the roof for environmental identification, this change in vehicle height has a negligible impact on freeway geometric design. In a fully autonomous driving environment, the vehicle types in the traffic flow do not change. The size, weight, function, structure, and engine configuration of the vehicle have also not changed significantly. The difference is that all aspects of the vehicle's control system and performance have been improved, reducing driving safety factors, so that the current standards can also be used in an autonomous driving environment. Take the Chinese *Design Specification for Highway Alignment* as an example, as shown in Table 2.

Table 2. Dimensions of vehicle designs.

Vehicle Design Type	Dimensions (m)					
	Length	Width	Height	Front Overhang	Wheelbase	Rear Overhang
Passenger car	6	1.8	2	0.8	3.8	1.4
Large bus	13.7	2.55	4	2.6	6.5 + 1.5	3.1
Articulated bus	18	2.5	4	1.7	5.8 + 6.7	3.8
Trucks	12	2.5	4	1.5	6.5	4
Articulated semitrailer	18.1	2.55	4	1.5	3.3 + 11	2.3

3.3. Stopping Sight Distance

3.3.1. Braking Process

From the perspective of vehicle kinematics, a human-driven vehicle's (HDV's) braking process is affected by the driver's characteristics, so that brake reaction time (reaction distance) occurs. The whole braking process can be divided into three stages: driver perception and reaction stage, braking force rising stage, and full braking stage. Among them, driver perception and reaction stage start from the driver's recognition of a danger signal and lasts until the vehicle starts to brake. The time spent in this stage is T1. This stage also includes three sub-stages. First, the driver visually receives and recognizes the risk factors, and this sub-stage is recorded as t1. Second, the driver decides to and applies the brakes, and this sub-stage is recorded as t2. Third, the brake clearance is eliminated, the vehicle starts to brake, and this sub-stage is recorded as t3. At the end of T1, the vehicle's speed is still initial speed V0, and the vehicle's deceleration is zero. The braking force rising stage starts from the end of T1, the vehicle's deceleration increases, and the vehicle's speed gradually decreases. This stage continues until the vehicle's braking force rises to the max, at which time the vehicle's speed is V1, the vehicle's deceleration is amax, and the time spent in this stage is T2. After that, the vehicle enters the full braking stage. At this stage, the vehicle's speed gradually decreases to the braking end vehicle speed V2, and the deceleration is always maintained at the maximum value amax. The time spent in this stage is T3.

The driving distance in the driver perception and reaction stage is T1, the driving distance in the braking force rising stage is T2, and the driving distance in full braking stage is T3. S1, S2, and S3 constitute the stopping sight distance ST. The human-driven vehicle's braking process is shown in Figures 2 and 3.

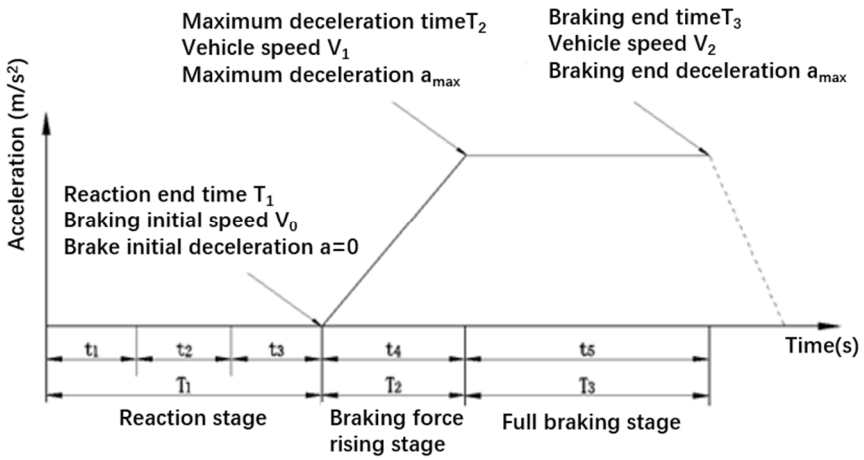

Figure 2. Relationship between braking deceleration and time.

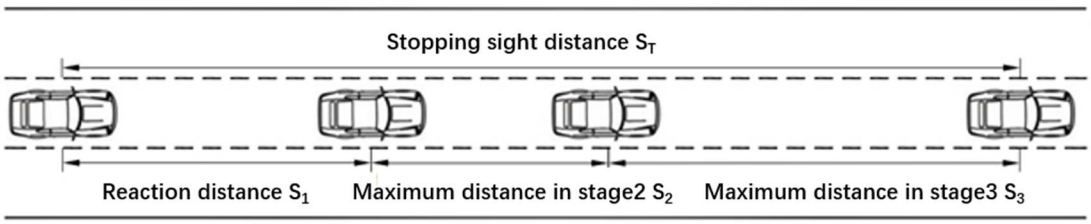

Figure 3. Schematic diagram of braking process.

In a fully autonomous driving environment, autonomous vehicles use sensors, cameras, and other identification systems to identify the road environment, with a wider field of view and higher identification accuracy than traditional drivers. The vehicle's brak-

ing, acceleration, deceleration, steering, and other actions are completed by the on-board computer system. The reaction process of the autonomous vehicles is simple and fast.

Many scholars at home and abroad have pointed out [26,27] that with the rapid development of artificial intelligence (AI), deep learning, and supercomputers, the CPU of autonomous vehicles can quickly identify the environment, intelligently make decisions, and efficiently control the vehicle. In the research on stopping sight distance of autonomous driving vehicles, a large number of machine simulation experiments and calculations have shown that the reaction time of autonomous driving vehicles is only about 0.5 s. Welde Y [10] used a 0.5 s system reaction time to calculate the stopping sight distance of L3 autonomous vehicles. In addition, Khoury J [28], when calculating the parking sight distance of autonomous vehicles, believed that the system reaction time of the autonomous vehicle from the moment it found the obstacle to the moment when the brakes took effect and started to decelerate was about 0.5 s.

To sum up, even if advanced technologies such as sensor systems, computers, and AI are used, autonomous vehicles will still take some time to collect road environment information, calculate, make decisions, and eliminate braking clearance. This means that autonomous vehicles also have reaction time and reaction distance. Therefore, the system reaction process cannot be directly ignored when calculating the stopping sight distance of autonomous vehicles.

3.3.2. Models and Calculations

Different countries have different models for calculating the stopping sight distance. According to the relevant literature [27,29], the calculation models of stopping sight distance in several representative countries have been summarized, as shown in Table 3. The calculation models of stopping sight distances in various countries are similar. There are only slight differences in the values of some parameters in the model.

Table 3. Calculation model of stopping sight distance in different countries.

Country	Calculation Model	Description
U.S.	$SSD = 0.278Vt + 0.039\frac{V^2}{a}$	SSD is stopping sight distance; V is design speed (km/h); t is reaction time; a is average deceleration.
France	$d_s = 2V + \frac{V^2}{2g\psi(v)}$	d_s is stopping sight distance; V is design speed (km/h); $\psi(v)$ is average deceleration (m/s^2); g is the acceleration of gravity (m/s^2).
China	$S_{sd} = \frac{V_0}{3.6} \cdot T + \frac{(V_0/3.6)^2}{2g \cdot f_1}$	S_{sd} is stopping sight distance; V_0 is driving speed (85% of design speed); f_1 is longitudinal friction coefficient; g is the acceleration of gravity (m/s^2).

- Reaction time

In a fully autonomous driving environment, because of the high speed, autonomous vehicles can travel long distances in a short time. Thus, the process of the system reaction cannot be simply ignored. Combined with relevant research, based on the principle of safety first, it is recommended to take the system reaction time of the autonomous vehicle as 0.5s when calculating the freeway stopping sight distance.

- Initial speed

A POLICY on GEOMETRIC DESIGN of HIGHWAYS and STREETS shows that many drivers do not greatly reduce their speed when the road is wet [30]. Thus, when calculating the stopping sight distance, the U.S. changed the initial speed during braking from the driving speed to the design speed. It can be seen from Table 3 that, like the United States, the initial speed in the French stopping sight distance model is also the design speed. Like Japan, China uses 85% of the design speed as the initial speed.

In a fully autonomous driving environment, the vehicle's sensor systems are less affected by the weather [10,31]. The driving speed is not limited by rainy weather and wet

and dry conditions of the pavement. At the same time, autonomous vehicles are expected to travel in line (at the same speed and a certain safe distance). This will greatly reduce frequent overtaking and lane changing behavior between vehicles. With the support of technologies such as the Internet of vehicles, CPUs, and high-precision maps, autonomous vehicles can globally plan driving routes in advance, so as to ensure driving speed and traffic efficiency. According to research [26], under the premise of road conditions and traffic regulations, autonomous vehicles can drive at the maximum speed. So, the initial braking speed is recommended to be taken as the design speed of a freeway.

- Deceleration

In the Chinese stopping sight distance calculation model, the value of braking deceleration considers the longitudinal friction coefficient between pavement and tires. However, research has shown that [27,32,33] the accurate measurement of the longitudinal friction coefficient needs to consider driving speed. During the measurement, the vehicle is fully braked, and the wheels are locked, which obviously does not correspond to the real braking process. With the advent of new pavement materials, tires, and ABS anti-lock braking systems, the longitudinal friction coefficient can no longer accurately reflect the real situation of emergency braking.

A POLICY on GEOMETRIC DESIGN of HIGHWAYS and STREETS made the following argument [30]: On slippery pavement, when decelerating and braking at a deceleration rate of 3.4 m/s^2, the vehicle can be well-controlled in its own lane, avoiding the impact on vehicles in other lanes. At the same time, most drivers will feel comfortable and safe. Most vehicle braking systems and the tire–pavement friction levels of most roadways are capable of providing a deceleration of at least 3.4 m/s^2 [11.2 ft/s^2]. The United States takes the deceleration in the stopping sight distance calculation model as 3.4 m/s^2, replacing the longitudinal friction coefficient in the old model. In the current German, American, and Australian alignment design specifications, the longitudinal friction coefficient has been replaced by braking deceleration, and its value is shown in Table 4 [27].

Table 4. Braking deceleration in foreign alignment design specifications.

Parameter	Country		
	U.S.	Germany	Australia
Average longitudinal deceleration (m/s^2)	3.4	3.7	2.55 (Comfortable braking)
			3.53 (Comfortable emergency braking)
			4.51 (Emergency braking)

In a fully autonomous driving environment, the vehicle's performance and the principle of the braking system have not changed qualitatively. So, it is not recommended to use the friction coefficient to calculate the stopping sight distance. At the same time, combined with the latest research [10,28,34], Khoury J et al. still used 3.4 m/s^2 deceleration to calculate the stopping sight distance of autonomous vehicles. When Welde Y et al. calculated the stopping sight distance of L3 autonomous vehicles, the braking deceleration was taken as 3.4 m/s^2; when they calculated the stopping sight distance of L5 autonomous vehicles, they believed that the control performance of the autonomous vehicle would be better than the average level of drivers expected by AASHTO, so they took braking deceleration as 4.5 m/s^2. In addition, Durth W et al. [34] also proposed calculating the stopping sight distance with a braking deceleration of 4.5 m/s^2.

The calculation of the stopping sight distance should comprehensively consider the rationality of the calculation method and value of braking deceleration, the uncertainty of deceleration in the braking force rising stage, and the influence of deceleration value on passenger comfort. Based on the above research, according to the braking characteristics of the autonomous vehicle, this paper proposes using average deceleration instead of the friction coefficient to calculate the stopping sight distance. In order to meet the braking safety and the comfort requirements of passengers, the average deceleration is taken as 3.4 m/s^2.

The stopping sight distance of autonomous vehicles consists of two parts, the reaction distance and the braking distance, and its calculation is shown in Formula (1) [30]:

$$S_{st} = S_{re} + S_b = \frac{V}{3.6} \cdot t + \frac{(V/3.6)^2}{2a_{max}} \quad (1)$$

where S_{st} is the stopping sight distance(m), S_b is the braking distance (m), V is the design speed, t is the system reaction time, taken as 0.5s, and a_{max} is the maximum braking deceleration, taken as 3.4 m/s^2.

According to Formula (1), the recommended value of stopping sight distance of passenger cars in an automatic driving environment is calculated as shown in Table 5. The stopping sight distance of each lane at each design speed of freeway shall not be less than the provisions in Table 5.

Table 5. Stopping sight distance based on automatic driving technology.

Design Speed (km/h)	Chinese Specified Value (m)	Calculated Value (m)	Suggested Value (m)
180	—	392.65	400
160	—	312.71	320
140	—	241.85	250
120	210	180.07	185
100	160	127.36	130
80	110	83.73	85

Compared with the stopping sight distance in the traditional manned driving environment, the stopping sight distance based on the automatic driving technology will be reduced by 25~30 m at each design speed, which is beneficial to economics of construction, as shown in Figure 4.

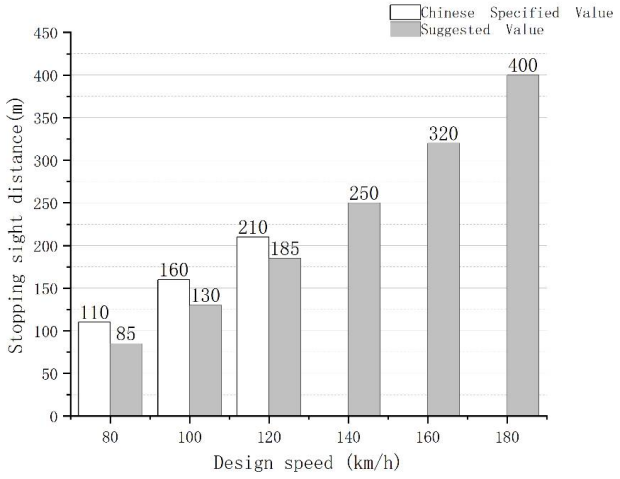

Figure 4. Comparisons of stopping sight distance.

3.3.3. Stopping Sight Distance of Trucks on a Downgrade

The braking distance of traditional vehicles varies with grades, and autonomous vehicles are no exception. The stopping sight distance in Table 5 does not consider the influence of grades. Its value is on the safe side for upgrades and dangerous for downgrades.

Especially for trucks, grades have an impact on their stopping sight distance, as shown in Formula (2) [35,36]:

$$S_{st} = \frac{V}{3.6} \cdot t + \frac{(V/3.6)^2}{2(a_{max} - i)} = \frac{V}{3.6} \cdot t + \frac{V^2}{254(\frac{a_{max}}{9.81} - i)} \quad (2)$$

where S_{st} is truck downhill stopping sight distance(m), i is the gradient (%), V is design speed (km/h); t is system reaction time, which is 0.5 s, and a_{max} is the maximum braking deceleration, which is 3.4 m/s^2.

Referring to the standards on maximum grade of various countries in the world [3] and combined with the research results of the maximum grade of freeways [23], this paper takes the maximum grade at design speeds of 140 km/h, 160 km/h, and 180 km/h as 3, 2, and 2%. According to Formula (2), the stopping sight distance of trucks on a downgrade in an autonomous driving environment is calculated, as shown in Table 6. Considering the dynamic performance of trucks, their maximum speed is lower than passenger cars. Therefore, the stopping sight distance of trucks at the design speeds of 160 km/h and 180 km/h is not calculated and specified.

Table 6. Stopping sight distance of automatic driving truck on downgrade.

Design Speed (km/h)	Downgrade (%)					
	0	**2**	**3**	**4**	**5**	**6**
140	250	260	265	—	—	—
120	185	195	200	205		
100	130	135	140	145	150	
80	85	90	95	95	100	100

3.4. Decision Sight Distance

The function of decision sight distance is to ensure that drivers who have not received the export notice information can change lanes in time, slow down, and then leave the main line before the exit of the interchange, parking area, or service area. Decision sight distance can prevent drivers from missing the exit due to his/her own negligence and ensure that vehicles travel on the expected route. When calculating decision sight distance, *A POLICY on GEOMETRIC DESIGN of HIGHWAYS and STREETS* believes that pre-handling time should be longer than reaction time in the stopping sight distance calculation model, so that drivers have enough time to deal with road traffic conditions. As an important design element to ensure that the vehicle follows the prescribed route and avoids drivers changing lanes or reversing near the exit, the application and efficacy of decision sight distance in an autonomous driving environment will make a big difference.

In a fully autonomous driving environment, with the cooperation of on-board sensors, CPU, and high-precision maps, autonomous vehicles can fuse, correct, and label information collected by multiple sensors. By positioning, marking signs, and road condition information, autonomous vehicles can achieve centimeter-level positioning [37,38]. According to relevant research [38,39], there are two types of route-planning methods for autonomous vehicles: global route planning and local route planning. Accurate and flexible local route planning can ensure that autonomous vehicles travel according to the optimal route planned between starting and ending points. At the interchange exit, global route planning tells autonomous vehicles where to go and which ramp to take off the main line. Local route planning guides autonomous vehicles to avoid obstacles, overtake, and change lanes by outputting control signals such as trajectory, speed, and steering angle. Two route planning methods cooperate with each other. This successfully solves the problems of drivers misjudging traffic information, making wrong decisions, not preparing to leave the main line in advance, and missing the interchange exit in the traditional driving environment.

To sum up, in a fully autonomous driving environment, vehicles can successfully identify the interchange exit without decision sight distance. At the exit, vehicles only need to decelerate and drive smoothly into the offramp without braking. Therefore, it is suggested that the geometric design of freeways at the exit of the interchange should no longer be bound and limited by decision sight distance and only needs to meet the stopping sight distance of autonomous vehicles.

4. Geometric Design Standard

This section studies the horizontal and vertical design indicators of autonomous freeways based on the requirements of the vehicle's driving sight distance, driving mode, and passenger comfort in the autonomous driving environment. By means of comparative and theoretical analysis, we determine the maximum and minimum length limits of straight lines, lane and hard shoulder widths, decision sight distance requirements, and gentle slope setting requirements for autonomous highways. At the same time, through the method of computational model research and theoretical calculation, we propose the minimum radius of circular curve, stopping sight distance, minimum length, and minimum radius of the vertical curve for autonomous driving freeways.

4.1. Horizontal Alignment

4.1.1. Maximum Tangent Length

When the vehicle runs on the tangent, the operation is simple, the direction is clear, the force on the vehicle is simple, and the driver experiences comfort. However, considering the driver's traffic characteristics and psychological and physiological factors, if the length of the tangent is not restricted, drivers who drive in a long shaft tangent for a long time are prone to overspeed, fatigue, relaxation of driving vigilance, and irritability, which are not conducive to driving safety [40,41].

However, in an autonomous driving environment, drivers no longer control the vehicle. The speed of vehicles is output in real time by an onboard computer system according to the road information and road conditions collected by the sensors. The tangent design of an autonomous driving freeway does not need to consider the driver's physiological and physical characteristics. It is only necessary to ensure that the alignment is compatible with the natural conditions and consider the economy of construction. Therefore, it is recommended to cancel the maximum tangent length.

4.1.2. Minimum Tangent Length

If the length of the tangent between two curves of identical direction is too short, the driver will be misled visually. This does not meet the principle of "alignment design should be continuous". In this respect, in a fully autonomous driving environment, the on-board camera will not produce the same misleading visual as the driver. The tangent length limit between two curves of identical direction is irrelevant.

Whether in a manual driving environment or autonomous driving environment, there are superelevation and widening transition requirements between two reverse curves. When an autonomous vehicle is driving on the reverse curve section of a freeway at high speed, it is necessary to avoid the instability caused by too short of a tangent between the reverse curves. At the same time, it is necessary to ensure that passengers adapt to changes of centrifugal force, so as to avoid an uncomfortable driving experience such as dizziness or shaking. Therefore, in an autonomous driving environment, it is suggested to limit the tangent length between reverse curves according to the current specification.

According to the driving characteristics of autonomous vehicles and referring to the current standard, in an autonomous driving environment, the minimum tangent length in the horizontal alignment design of freeways is limited, and its length (suggested value) is shown in Table 7.

Table 7. Tangent length based on autonomous driving technology.

Length Type		Design Speed (km/h)					
		80	**100**	**120**	**140**	**160**	**180**
Maximum tangent length (m)		—	—	—	—	—	—
Minimum tangent length (m)	Equidirectional curve	480	600	720	840	960	1080
	Reverse curve	160	200	240	280	320	360

4.1.3. Minimum Radius of Curve

As a common alignment element in horizontal alignment, the selection of curve radius should be in line with the design speed. For safety and comfort of driving, the Chinese *Design Specification for Highway Alignment* specifies the minimum radius of a curve according to Formula (3) [3,42]:

$$R = \frac{V^2}{127(\mu \pm i_h)} \quad (3)$$

where R is the radius of a curve (m); V is the design speed (km/h); μ is the lateral force coefficient; i_h is the superelevation value.

- Limited Minimum radius of curve

When calculating the limit minimum radius of a curve, the Chinese standard only considers the driving safety of a vehicle. It does not consider the requirements of stopping sight distance. This paper will study the minimum radius of a curve from two aspects: driving safety of autonomous vehicle and the requirements of lateral clear distance.

According to the Chinese *Design Specification for Highway Alignment*, considering the comfort of passengers, when the lateral force coefficient $\mu < 0.10$, passengers cannot feel the curve when they turn, and the vehicle is very stable; when $\mu = 0.15$, passengers can feel the curve slightly when turning, and the vehicle is relatively stable; when $\mu = 0.20$, passengers can feel the curve exists when turning, and the vehicle is slightly unstable; when $\mu = 0.35$, passengers can feel the curve exists when turning, and the vehicle is unstable; when $\mu > 0.40$, the vehicle is very unstable, and there is a risk of tipping over. Therefore, the value of μ must be limited when calculating the radius of the circular curve. In view of China's vast territory, geographical and climatic conditions vary greatly, so the standard needs to adapt to a variety of adverse conditions. In the Chinese *Design Specification for Highway Alignment* [35], on the basis of the most unfavorable situation when calculating the limit minimum radius of a freeway circular curve, the lateral force coefficients at the design speeds of 120 km/h, 100 km/h, and 80 km/h are taken as 0.10, 0.12, and 0.13. Obviously, the higher the design speed of a freeway, the more the passenger's comfort needs to be considered, so the restriction on the lateral force coefficient is also greater. Referring to the description of the meaning of the lateral force coefficient in the Chinese *Design Specification for Highway Alignment*, this paper takes the lateral force coefficients at design speeds of 140 km/h, 160 km/h, and 180 km/h as 0.09, 0.08, and 0.07 and then substituted them into Formula (3) to calculate the limit minimum radius in an autonomous driving environment, as shown in Table 8.

Table 8. Limit minimum radius of curve for traffic safety (m).

Design Speed (km/h)		180	160	140	120	100	80
Lateral Force Coefficient		0.07	0.08	0.09	0.10	0.12	0.13
Limit minimum radius of curve (m)	i_h =10%	1345	1120	910	570	360	220
	i_h =8%	1500	1260	1030	650	400	250
	i_h =6%	1700	1440	1200	710	440	270
	i_h =4%	1970	1680	1400	810	500	300

To meet the lateral clearance requirements, in a fully autonomous driving environment, a certain lateral clearance of curve shall be provided for the freeway excavation section to ensure that the sensor systems can normally find the way and detect the road condition information ahead, as shown in Figure 5. In this way, the security risk caused by a communication system failure or information transmission delay can be reduced, and the driving speed and traffic efficiency of an autonomous vehicle fleet can be guaranteed.

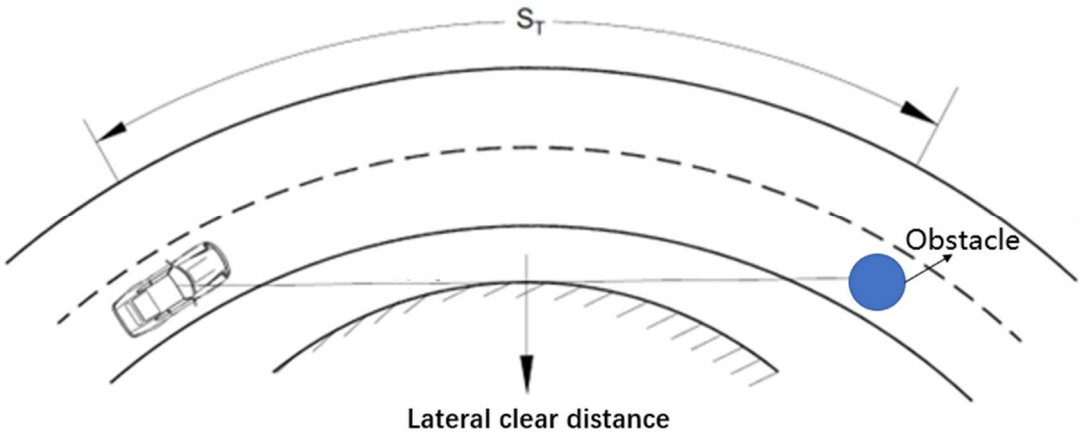

Figure 5. Demand for lateral clear distance of autonomous driving freeway.

The required radius of a curve can be calculated from the stopping sight distance and the lateral clearance provided by an autonomous driving freeway. The relationship between the three is shown in Formula (4).

$$m = R\left[1 - \cos\left(\frac{28.65S_t}{R}\right)\right]. \quad (4)$$

Here, m is the lateral clear distance (m); R is the radius of a curve at the centerline of the lane within the curve (m); S_t is the stopping sight distance (m), according to the recommended value in Section 3.3.

According to Section 4.2.2, the apparent height of an autonomous driving passenger car is taken as 1.85 m. It can be seen from Section 4.3 that the demand for the lane width and width of shoulder will not increase due to the increase of driving speed. The lane width and width of shoulder at different design speeds are not exactly the same. When the design speed is 80~120 km/h, in the most conservative case, the lane width needs to meet the requirement of 3.5 m for large vehicles, and the width of shoulder only needs 1.5 m; when the design speed is 140~180 km/h, in the most conservative case, the lane width needs to meet the requirement of 3.75 m for large vehicles, and the width of shoulder needs 3 m.

For the above reasons, the lateral clearance provided on the inside of curve is divided into two cases:

1. When the design speed is 80~120 km/h, the lateral clear distance (in the most conservative case) on the inside of the curve of the excavation section is 3.5 (driveway width)/2 + 1.5 (paved shoulder) + 0.75 (soil shoulder) + 0.6 (side ditch) + 1.00 (crushing platform) + 1.85 × 0.75 = 6.9875 m.
2. When the design speed is 140~180 km/h, the lateral clear distance (in the most conservative case) on the inside of the curve of the excavation section is 3.75 (driveway width)/2 + 3 (paved shoulder) + 0.75 (soil shoulder) + 0.6 (side ditch) + 1.00 (crushing platform) + 1.85 × 0.75 = 6.9875 m.

Taking the relevant calculation parameters into Formula 4, the minimum radius of the curve at each design speed of the excavation section can be calculated, and the results are shown in Table 9.

Table 9. Limit minimum radius of curve for lateral clearance requirements (m).

Design Speed (km/h)	Stopping Sight Distance (m)	Minimum Radius (m)
180	400	2320
160	320	1485
140	250	905
120	185	610
100	130	320
80	85	145

Compare Tables 8 and 9 and take the larger value in the table (rounded up) as the limit minimum radius of a curve, as shown in Table 10.

Table 10. Limit minimum radius of curve based on autonomous driving technology (m).

Design Speed (km/h)		180	160	140	120	100	80
Limit minimum radius of curve (m)	Meet the requirements of traffic safety	1500	1260	1030	650	400	250
	Meet lateral clearance requirements	2320	1485	905	610	320	145
	Limit minimum radius	2350	1500	1030	650	400	250

The limit minimum radii of a curve with the design speeds of 80 km/h, 100 km/h, and 120 km/h in the Chinese specification are 250, 400, and 650, which are the same as the calculated values in the table. This is because, when the design speed is low, the limit minimum radius is mainly affected by the dynamic characteristics of vehicles. At the same time, the dynamic characteristics of fully autonomous vehicles change little, so the calculated value of the limit minimum radius does not change. However, when the design speed is high, the most important factor affecting the limit minimum radius changes from the dynamic characteristics to the demand for the lateral clearance.

- General minimum radius of curve

The general minimum radius of a curve in the Chinese *Design Specification for Highway Alignment* is used to ensure driving comfort. Considering the passenger's comfort and experience, referring to Chinese standards, this paper takes the lateral force coefficient as 0.05 and the superelevation value as 6%, which are substituted into Formula (4) and rounded up. The results are shown in Table 11.

Table 11. General minimum radius of curve based on autonomous driving technology (m).

Design Speed (km/h)	180	160	140	120	100	80
General minimum radius of curve (m)	2500	2000	1500	1050	750	500

The general minimum radii of a curve with the design speeds of 80 km/h, 100 km/h, and 120 km/h in the Chinese specification are 400, 700, and 1000. In contrast, the general minimum radii of curves based on autonomous driving technology increase by 100, 50, and 50. This shows that autonomous vehicles have higher requirements for passenger comfort.

- Minimum radius of curve without superelevation

This paper refers to the Chinese *Design Specification for Highway Alignment* to calculate the lateral force coefficient and superelevation value of a curve without a superelevation minimum radius. When the cross slope is less than 2%, take $\mu - i_h = 0.02$; when the cross slope is more than 2%, take $\mu - i_h = 0.015$. Substitute it into formula (4) and round it up. The results are shown in Table 12.

Table 12. Minimum radius of curve without superelevation (m).

Design Speed (km/h)		180	160	140	120	100	80
Minimum radius of curve without superelevation (m)	Cross slope $\leq$ 2%	12,800	10,100	7750	5500	4000	2500
	Cross slope > 2%	17,050	13,500	10,300	7500	5250	3350

The minimum radius of curve without superelevation at the design speeds of 80 km/h, 100 km/h, and 120 km/h when the cross slopes of less than 2% in the Chinese standard are 2500, 4000, and 5500, which are the same as the calculated values in the table. When the cross slope is greater than 2%, the minimum radius of curve without superelevation with the design speeds of 80 km/h, 100 km/h, and 120 km/h are 3350, 5250, and 7500, which are the same as the calculated values in the table.

4.1.4. Maximum Radius of Curve

Under the traditional artificial driving environment, when a driver is driving on a curve section with large radius and long length, the force state of the vehicle and the psychological and physiological characteristics of the driver are almost the same as driving on a long straight road. The large radius curve can shorten the mileage and save the engineering cost more than the small radius curve. However, in plains or deserts and other monotonous roadside landscape sections, if driving on a large-radius circular curve for a long time, drivers are prone to fatigue, boredom, and irritability. This will lead to overtaking and speeding. In addition, due to long-time high-speed driving, drivers are prone to perception errors and unresponsiveness, which are not conducive to driving safety. In view of this, the current standards of various countries also limit the maximum radius of curves.

In an autonomous driving environment, there is no need for a human to operate the vehicle. An autonomous vehicle is controlled by an autonomous driving system, which consists of technologies such as a CPU, vehicle-borne radar and image recognition, AI, and deep learning. During driving, there is no driver's boredom, overspeeding, decreased perception, and other conditions that affect driving safety. From the economic point of view, the use of a large radius horizontal curve can shorten the mileage, thus saving land resources. Therefore, in a fully autonomous driving environment, considering the driving safety and passenger comfort, it is recommended to cancel the limit on the maximum radius of curves.

4.2. Vertical Alignment

4.2.1. Transition Slope

At present, different scholars have different views on whether it is scientific and reasonable to set a transition slope between long and steep slopes. Liu Ge [43] found through the simulation experiment that when the average longitudinal slope of the road is large, the transition slope can play a role in restoring the speed of trucks on the slope. Wang Z [44] and others believe that some European countries tend to design a single longitudinal slope, mainly because the transition slope will make drivers relax their vigilance. Pan X [45] put forward the suggested values of the transition slope gradient and slope length at different altitudes. It can be seen that most scholars are quite sure of the positive effect of the transition slope section in an upgrade.

Compared with the traditional self-driving vehicle, the dynamic performance of the autonomous vehicle does not change qualitatively in the autonomous driving environment. Second, the autonomous vehicle's "eyes" have become sensors. In other words, the insertion of transition slopes between consecutive downhill sections will not cause the illusion of flatness or an anti-slope. It is conducive to downhill vehicle deceleration. Therefore, this paper refers to the maximum longitudinal slope value of each design speed of superhighway [23], combined with the stipulations of each country, and the maximum

longitudinal slopes at design speeds of 140 km/h, 160 km/h, and 180 km/h are 3%, 2%, and 2%. Through the analogy analysis, the setting requirements of the transition slope at each design speed are obtained, as shown in Table 13.

Table 13. Gradient of transition slope.

Gradient	Design Speed (km/h)					
	80	100	120	140	160	180
Maximum gradient of transition slope (%)	3	2.5	2.5	2.5	—	—

4.2.2. Convex Vertical Curve

The minimum radius of the vertical curve is mainly controlled by the combination of impact mitigation, driving time, and sight distance. In calculating the minimum radius of the convex vertical curve, the sight distance is the key control factor. The calculation processes are as follows [3]:

1. The calculation diagram for when the stopping sight distance is more than the length of the vertical curve is shown in Figure 6.

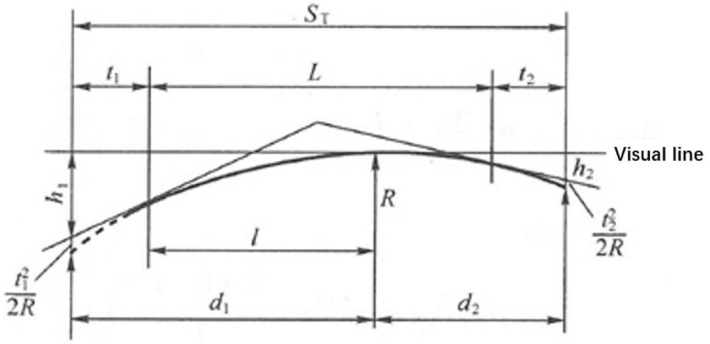

Figure 6. Schematic diagram of convex vertical curve calculation.

According to Figure 6, Formula (5) can calculate the minimum radius that satisfies the sight distance requirement:

$$\left.\begin{array}{c} S_T = \frac{R}{L}\left(\sqrt{h_1}+\sqrt{h_2}\right)^2 + \frac{L}{2} = \frac{\left(\sqrt{h_1}+\sqrt{h_2}\right)^2}{\omega} + \frac{L}{2} \\ L_{\min} = 2S_T - \frac{2\left(\sqrt{h_1}+\sqrt{h_2}\right)^2}{\omega} \end{array}\right\} \quad (5)$$

where S_T is the stopping sight distance (m); $L_{\min}$ is the minimum length of the vertical curve (m); R is the radius of the vertical curve (m); h_1 is the driver's visual height, which is 1.2 m; h_2 is the obstacle height, which is 0.1 m; L is the vertical curve length (m); ω is algebraic gradient difference between adjacent straight sections.

2. The calculation diagram for when the stopping sight distance is less than the length of vertical curve is shown in Figure 7.

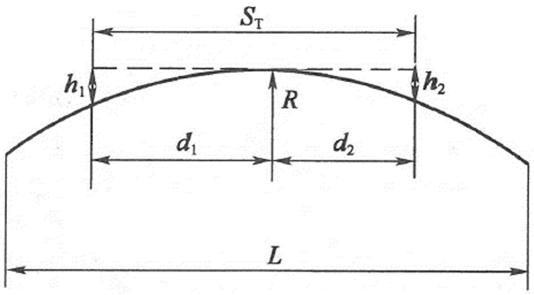

Figure 7. Schematic diagram of convex vertical curve calculation.

According to Figure 7, Formula (6) can calculate the minimum radius that satisfies the sight distance requirement:

$$\left.\begin{array}{c} S_T = \sqrt{2R}\left(\sqrt{h_1} + \sqrt{h_2}\right) \\ L_{\min} = \frac{{S_T}^2\omega}{2\left(\sqrt{h_1}+\sqrt{h_2}\right)^2} \end{array}\right\} \quad (6)$$

where the parameter meanings are the same as before.

When calculating the minimum radius of the convex vertical curve, the most conservative case should be selected, that is, the equation with a larger $L_{\min}$ value should be used. Subtract Formula (6) from Formula (5) and bring the values of h_1 and h_2 into the formula.

$$L_{\min 1} - L_{\min 2} = 2S_T - \frac{4}{\omega} - \frac{{S_T}^2\omega}{4} = -\frac{(S_T\omega - 4)^2}{4\omega} \quad (7)$$

Obviously, the calculation result $L_{\min 2}$ of Formula (6) is larger than the calculation result $L_{\min 1}$ of Formula (5). Accordingly, this paper chooses Formula (6) (vertical curve length is greater than the stopping sight distance) to calculate the minimum radius of the convex vertical curve.

- Satisfy sight distance requirements

Autonomous vehicles may also have blind spots when driving on a convex vertical curve, similar to traditional manual driving, as shown in Figure 8. When designing a convex vertical curve, to ensure driving safety, it is necessary to meet the stopping sight distance requirements of an autonomous vehicle. The calculation models and method for convex vertical curves in the design specifications of various countries are also applicable to the autonomous driving environment. The difference is the variation of some parameters in the formula, such as the visual height of autonomous vehicle elevation, stopping sight distance requirement, and so on.

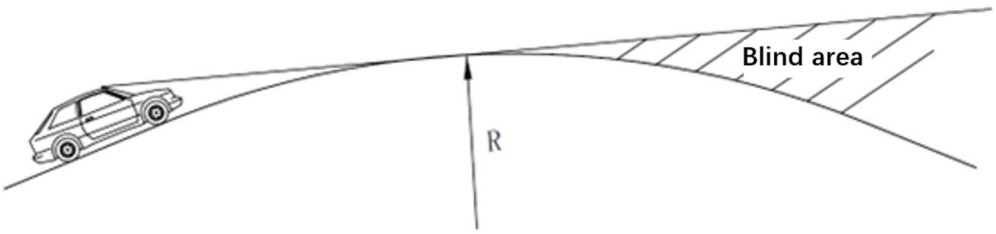

Figure 8. Blind area of convex vertical curve.

In Formula (6), h_1 is the visual height. Autonomous vehicles are no longer controlled by the driver but by a variety of on-board sensors and CPUs. The position and height of its viewpoint change accordingly, as shown in Figure 9. Both the Hong Qi and Uber autonomous vehicles have video cameras and radar sensors positioned on the roof.



(**a**) (**b**)

Figure 9. The autonomous vehicles of different brands. (**a**) Uber autonomous vehicle. (**b**) Hong Qi autonomous vehicle.

In the age of autonomous driving, autonomous vehicle eyes were replaced by LiDAR sensors. When calculating the minimum length of a convex vertical curve on an autonomous driving road [10], the autonomous vehicle is considered to be the same height as a 1.555 m tall SMART car. The height of the LiDAR is 0.283 m, so the visual height of the autonomous vehicle is 1.838 m. Google's autonomous driving project tested LiDAR on Toyota and Lexus RX450H autonomous vehicles, which were 1.470 m and 1.685 m [24]. Khoury J [28] used the visual height of 2.27 m (vehicle height is 1.685 m, the height of radar sensor is 0.284 m, and the support height of the sensor is 0.3 m.) for the Lexus RX450h (SUV) and 1.84 m (vehicle height is 1.555 m, the height of radar sensor is 0.284 m, and the support height of sensor is not considered) for the Waymo autonomous vehicle when calculating the minimum length of a convex vertical curve. Autonomous driving passenger cars will be larger and taller than SMART cars, as will autonomous driving SUVs, trucks, and buses. The higher the visual height of vehicles, the lesser need for the length of the vertical curve. Taking the above factors into consideration, scholar Khoury J conservatively takes the visual height of autonomous vehicles as 1.7 m.

According to the above research, considering continuous development of technology and optimal design of sensors, the sensor height is chosen as 0.25 m. Normal passenger cars are typically less than 1.55 m tall, and SUVs are about 1.80 m tall. Due to the tolerance of safety, the height of the autonomous vehicle is rounded to 1.60 m from 1.55 m. Therefore, the visual height h_1 of the autonomous driving passenger car is the sum of the above two heights, which is taken as 1.85 m (vehicle height 1.60 m and sensor height 0.25 m).

In Formula (6), h_2 is the height of the obstacle. The minimum height of the car chassis from the ground is 0.14~0.2 m [3]. On the one hand, autonomous vehicles are much better than drivers at recognizing road conditions. On the other hand, very small obstacles can cause a vehicle to lose control in a high-speed environment. Referring to Chinese standards, the obstacle height is still taken as 0.1 m in this paper.

In Formula (6), S_T is the stopping sight distance. This paper adopts the recommended stopping sight distance based on automatic driving technology in Section 3.3.

- Meet the impact mitigation requirements

When an autonomous driving car travels at a high speed on a vertical curve, it can become overweight or weightless. When the phenomenon of becoming overweight or weightlessness reaches a certain degree, passengers will have uncomfortable psychological and physiological reactions. It will also bring adverse effects on the car's suspension system. Accordingly, in the autonomous driving environment, it is recommended to continue to apply the minimum radius value of the vertical curve in current specifications that considers alleviating impact, as shown in Formula (8):

$$R_{\min} = \frac{V^2}{3.6} \text{ or} L_{\min} = \frac{V^2}{3.6} \cdot \omega \tag{8}$$

where $R_{\min}$ is the minimum radius of the vertical curve (m); $L_{\min}$ is the minimum length of the vertical curve (m); V is the design speed (km/h); ω is the algebraic gradient difference between adjacent straight sections.

- Meet the requirements of travel time

In traditional manual driving environment, when the length of the vertical curve is very short, if the car is driving at a high speed through this section of the road, the driver is prone to the illusion of a large slope, and passengers will also feel uncomfortable. In an autonomous driving environment, although there is no driver's visual illusion, passengers will still feel uncomfortable. It is also recommended to continue to apply the provisions of current standards to ensure that the driving time of autonomous vehicles on the vertical curve should not be too short, as shown in Formula (9):

$$L_{\min} = \frac{V}{3.6} \cdot t = \frac{V}{1.2} \tag{9}$$

where L_{min} is the minimum length of the vertical curve (m); V is the design speed (km/h); t is travel time, taken as 3 s.

The minimum radius and minimum length of convex vertical curve at each design speed are calculated from Formulas (6), (8), and (9), as shown in Table 14. Considering the comfort and physiological feeling of passengers at high speeds, the general value of the vertical curve radius in table is 1.5–2 times that of the minimum value, and the minimum length is 3 s of travel at the design speed. From Table 14, it can be seen that the vertical curve radius of freeways at various design speeds are mainly controlled by sight distance in an autonomous driving environment.

Table 14. The minimum radius and minimum length of convex vertical curve.

Design Speed (km/h)	Calculated Value of Vertical Curve Length			Suggested Value		
				Radius s(m)		Length (m)
	Sight Distance	Impact Mitigation	Travel Time	Minimum Value	General Value	Minimum Value
180	$28,470\omega$	9000ω	150	28,500	43,000	150
160	$18,221\omega$	7111ω	133	18,250	27,500	135
140	$11,121\omega$	5444ω	117	11,150	17,000	120
120	6090ω	4000ω	100	6100	9500	100
100	3004ω	2778ω	83	3000	4500	90
80	1286ω	1778ω	67	2000	3000	70

The minimum radii of the convex vertical curve with the design speeds of 80 km/h, 100 km/h, and 120 km/h in the Chinese standard are 3000 m, 6500 m, and 11,000 m, respectively. Compared with the radius requirement of a convex vertical curve in the traditional driving environment, the minimum vertical curve radius based on autonomous driving technology is reduced by 1000 m, 3500 m, and 4900 m at 80 km/h, 100 km/h, and 120 km/h design speeds, as shown in Figure 10. To a certain extent, this saves the construction cost of autonomous driving freeways.

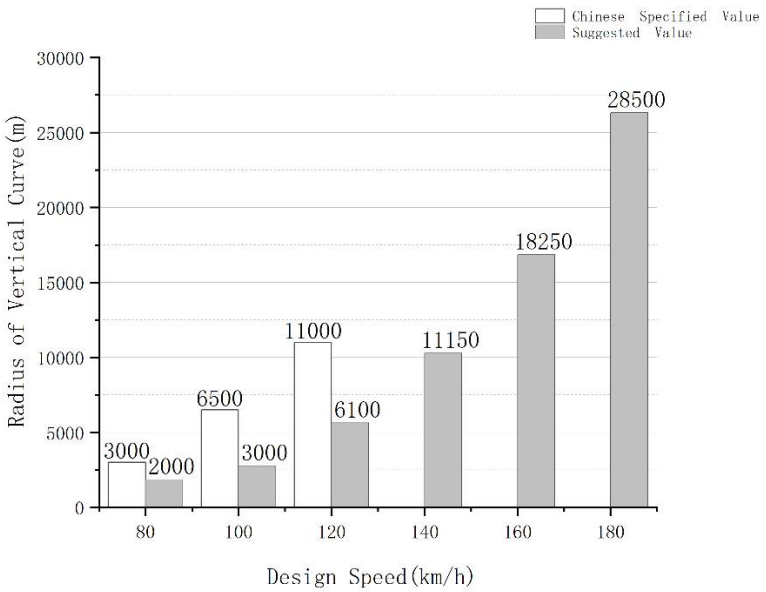

Figure 10. Comparison of limited minimum radius of vertical curve.

The minimum value of the vertical curve radius of 28,500 m given in this article can only ensure that the vehicle runs relatively smoothly and cannot ensure that the

passengers have a high degree of comfort. Therefore, this value should only be used in places where terrain conditions are more restrictive, such as mountains, and it requires strict argumentation when using it. In order to ensure the comfort of passengers, the designer should take the general value of the vertical curve radius of 43,000 m as the control index. The general value is the recommended value for the safety and comfort of the vehicle running at the design speed.

4.2.3. Concave Vertical Curve

A concave vertical curve is mainly affected by sight distance requirements for vehicles under overpass bridges and sight distance requirements at night. In an autonomous traffic environment, Welde Y [10] noted in his study that the Waymo team has developed a range of sensors that enable autonomous vehicles to detect 360-degree environments both during the day and at night. In other words, at night, an autonomous vehicle's radar sensors work as well as they do during the day, so vehicles are no longer limited by headlight illumination distance at night. In his research, Khoury J [28] believed that the function of headlights was replaced by sensors on the roof. Therefore, when studying the minimum radius of a concave vertical curve, this paper does not consider the requirement of headlight illumination distance; it only considers travel time, impact mitigation, and sight distance requirements for vehicles under overpass bridges. Since the requirements for cushioning impact and minimum travel time are the same for a convex vertical curve, it is only necessary to focus on sight distance requirements for vehicles under overpass bridges. The blind area under an overpass is shown in Figure 11.

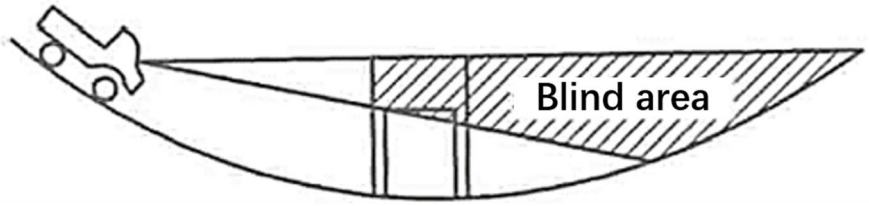

Figure 11. Blind area under an overpass.

In calculating sight distance requirements for vehicles under overpass bridges, *Design Specification for Highway Alignment* uses the results of calculation when the vertical curve length is not less than the stopping sight distance as an effective basis. The schematic diagram of calculation is shown in Figure 12.

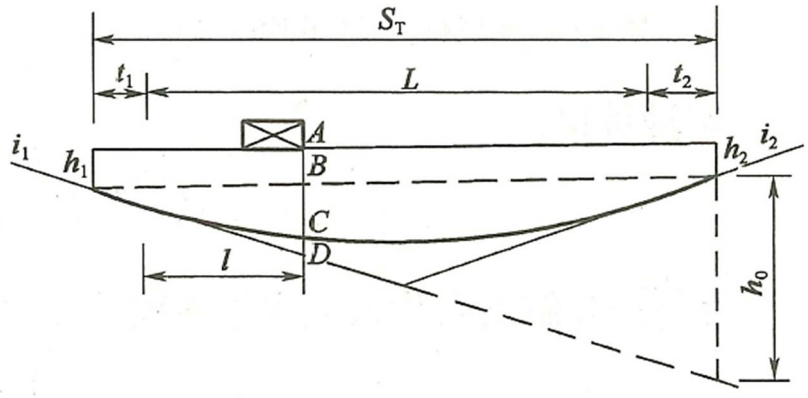

Figure 12. Calculation of radius of concave vertical curve under overpass bridge.

According to Figure 12, the minimum length of the concave vertical curve can be calculated by Formula (10):

$$\left.\begin{array}{c} L_{\min} = \dfrac{{S_T}^2 \omega}{\left[\sqrt{2(h_{\max}-h_1)}+\sqrt{2(h_{\max}-h_2)}\right]^2} \\ R = L/\omega \end{array}\right\} \quad (10)$$

where $L_{\min}$ is the minimum length of the vertical curve (m); S_T is stopping sight distance (m); $h_{\max}$ is the clearance under the bridge; h_1 is driver's visual height; h_2 is the height of the obstacle; ω is algebraic gradient difference between the adjacent straight sections.

In calculation, the parameters are taken according to Chinese current specifications. Combined with the results of Section 4.2.2, the visual height of an autonomous vehicle is 1.85 m (vehicle height is 1.60 m, and sensor height is 0.25 m), obstacles' height is 0.75 m, and the design clearance under the highway bridge is 5.0 m.

The minimum radius and minimum length of a concave vertical curve at each design speed are calculated from Formulas (8)–(10), as shown in Table 15. Considering the comfort and physiological feelings of passengers at high speeds, the general value of the vertical curve radius in the table is 1.5–2 times that of the minimum value, and the minimum length is 3 s of travel at design speed.

Table 15. The minimum radius and minimum length of concave vertical curve.

Design Speed (km/h)	Calculated Value of Vertical Curve Radius		Calculated Value of Vertical Curve Length	Suggested Value		
				Radius (m)		Length (m)
	Sight Distance	Impact Mitigation	Travel Time	Minimum Value	General Value	Minimum Value
180	9334ω	9000ω	150	9500	14,500	150
160	5974ω	7111ω	133	7500	11,500	135
140	3646ω	5444ω	117	5500	8500	120
120	1997ω	4000ω	100	4000	6000	100
100	1063ω	2778ω	83	3000	4500	85
80	473ω	1778ω	67	2000	3000	70

The minimum radii of the concave vertical curve with the design speeds of 80 km/h, 100 km/h, and 120 km/h in Chinese specifications are 2000 m, 3000 m, and 4000 m, and the minimum lengths of the vertical curve are 70 m, 85 m, and 100 m, which are the same as the recommended values in the above table. It can be seen from the above table that when the design speed is lower than 160 km/h, the radius of a concave vertical curve is mainly affected by impact mitigation; when the design speed reaches 180 km/h, the radius of concave a vertical curve is mainly affected by the sight distance requirement.

4.3. Cross-Section Elements

4.3.1. Lane Width

In different countries, the lane width of freeways is usually between 3 and 4 m.

As can be seen from Table 16, the Chinese freeway lane width is relatively large compared to other countries and is consistent with Germany's open-speed freeway lane width. The lane width regulation in China is based on the Poliankefu model. *Design Specification for Highway Alignment* establishes a model between the lateral width and speed based on the measured data of China's road traffic environment, as shown in Equations (11)–(13) [3]:

$$y = 0.0103V_1 + 0.56 \quad (11)$$

$$D = 0.000066\left({V_2}^2 - {V_1}^2\right) + 1.49 \quad (12)$$

$$M = 0.0103V_2 + 0.46 \quad (13)$$

where D is the safety distance between the edges of the rear wheels of two vehicles (m); M is the safety distance from the outer edge of the left rear wheel to the left side of the lane (m); y is the safety distance from the outer edge of the right rear wheel to the right side of the lane (m); V_2 and V_1 are the speed (km/h) of the overtaking vehicle and the vehicle being overtaken.

Table 16. Lane width specified by different countries (m).

Country	U.S.	Japan	Germany	China
Lane width (m)	3.6	3.5	3.5~3.75	3.75

It can be seen from this model that lane width is positively correlated with speed. In the autonomous driving environment, the driving speed of the vehicle will achieve further breakthroughs. If the lane width of the autonomous driving freeway is still calculated according to this model, it will cause unnecessary waste. It also does not match the real need for lane width in autonomous vehicles.

Wang Lei et al [46], in their research on lane width, believed that the demand for lane width would be reduced for cars equipped with a lane-keeping assistance system. Their results divide the lane lateral width into safety width and swing width, which includes performance pendulum and driving pendulum (swing caused by the driver steering). Pan Binghong [47] established a model of the lateral safety distance and speed difference between different vehicles based on the trajectory data of the vehicle. The results of study found that lane width specified in the Chinese *Design Specification for Highway Alignment* is too large. Many domestic scholars [48–50] reach the conclusion that the lane width in China is on the large side by analyzing the irrationality of the application of the Poliankefu model in the calculation of the road width of our country.

In an autonomous driving environment, the vehicle's running state will be more stable, and the speed change will be smoother. With the rapid development of the automobile industry, the driving stability of vehicles will be better and better. For autonomous vehicles, the driving pendulum caused by the drivers no longer exists, and the swing width of the vehicle will be effectively controlled. The lateral distance between parallel vehicles is reduced. The autonomous vehicle can sense the driving state of the surrounding vehicles in all directions. During the overtaking process, the autonomous vehicles, with the assistance of the on-board system, can keep moving at a suitable acceleration in the center of the lane, thus reducing the lateral distance requirement during the vehicle adjustment process. In addition, in a fully autonomous driving environment, it is hoped that different types of vehicles will be able to drive in line at the same speed. In other words, in the future, passenger cars, buses, and trucks can drive in separate lanes, which will greatly reduce the frequency of overtaking and lane-changing vehicles. On freeways with separate lanes, the width of the lane can be regulated according to the lane function, which can reduce the land use and save the cost of road construction.

To sum up, the need for driving width in autonomous vehicles does not increase as the speed increases. The lane width of an autonomous driving freeway will no longer consider driver's characteristics and driving sway, so the vehicle's lateral safe distance requirements will be reduced. Based on the lane width regulation of other countries and related research results, this paper suggests that lane width should be regulated according to lane function at different design speeds, as shown in Table 17. Considering the performance differences between small-sized vehicles and large-sized vehicles, on autonomous driving freeways with design speeds of 160 km/h and 180 km/h, each lane can only pass a single type of vehicle, and mixed lanes will no longer be set up to ensure efficiency.

Table 17. Autonomous driving freeway lane width (m).

Design Speed (km/h)		180	160	140	120	100	80
Single Lane width (m)	Small-sized vehicles	3.75	3.5	3.5	3.5	3.5	3.25
	Large-sized vehicles	3.75	3.75	3.75	3.5	3.5	3.5
Mixed lane width(m)		—	—	3.75	3.5	3.5	3.5

4.3.2. Width of Shoulder

According to Section 3.3.1, in an autonomous driving environment, the lane widths of freeways at different design speeds are not exactly the same. On the freeways with high design speed, the separation of passenger cars and trucks will be strictly implemented. Since the speed of passenger cars is much higher than trucks, if a broken-down truck stays in the truck lane at low speed for a long time, the vehicles in the truck lane will not be able to change lanes to the adjacent passenger lane. This will seriously affect the capacity of autonomous freeways. Therefore, the width of the hard shoulder should meet the need for large vehicles to pull over, so as to ensure traffic capacity and smoothness.

When the design speed is small, freeways set up mixed driving lanes. The driving speed of trucks and passenger cars in their lanes is not much different, which can provide favorable conditions for trucks to join. When there is a troubled vehicle in front of the lane, the truck behind can receive the relevant information in time and then decelerate and brake in advance or carry out local route planning, change lanes, and merge into mixed lanes to improve road traffic efficiency. The lane's capacity will be restored when the faulty vehicle enters the emergency parking strip. Obviously, when the design speed is small, the faulty vehicle has little effect on the road capacity. To reduce road construction costs, a combination of a narrow hard shoulder and emergency stop strip can be considered.

In this paper, based on traffic characteristics of autonomous vehicle roads, considering the value of hard shoulder width in China, as well as the economy of highway construction, the suggested width of the right shoulder of automatic driving freeways is put forward, as shown in Table 18. When the width of shoulder is 1.5 m, it is necessary to set an emergency parking strip.

Table 18. Width of right shoulder in autonomous freeways (m).

Design Speed (km/h)	180	160	140	120	100	80
Width of right shoulder (m)	3	3	3	1.5	1.5	1.5

5. Discussion

As a product of the development of Internet-of-vehicles technology, autonomous vehicles will change people's traditional concepts and methods of transportation. However, the current road design standards are formulated on the premise of manned driving, comprehensively considering various factors such as driver characteristics and vehicle characteristics. A driver's psychological and physiological factors will not be considered in the fully autonomous driving environment. This will inevitably lead to the phenomenon that the current design indicators are inconformity and uneconomical in the new driving environment. Therefore, the existing road geometric design standards need to be innovated to match the new requirements.

Firstly, in this study, we examine how some design elements change in a fully autonomous driving environment. These design elements are the basis of road geometric design and are usually directly influenced by driver factors. Design speed is the most important indicator in freeway geometric design. Without the constraints of a driver, the design speed will be further improved. Sight distance is mainly affected by the driver's reaction time. With sensors replacing human eyes, autonomous vehicles can identify road conditions and make decisions faster. By analyzing and improving the sight distance calculation model, it is found that the sight distance demand for autonomous vehicles will

be reduced. After summarizing the autonomous driving projects of various companies, we found that the appearance and performance of autonomous vehicles are not much different from traditional vehicles. Accordingly, the vehicle design indicator can continue to use the current standard.

Secondly, we study the horizontal and vertical alignment indicators. These indicators directly determine the shape of the road and affect the passenger experience and the economy of the construction. These alignment indicators are usually controlled by design speed, sight distance, and other indicators. Driver factors indirectly affect road alignment by influencing design elements. Unlike humans, an autonomous driving system has no visual illusion and will not overspeed or overtake frequently. The purpose of limiting the maximum length of straight lines and the maximum radius of curves is to avoid adverse effects on driver's physiology. In autonomous vehicles, there is no driver. Therefore, from the perspective of driving safety and passenger comfort, we recommend removing the restrictions on the maximum length of straight lines and the maximum radius of curves. The current standard only considers the vehicle force balance when calculating the radius of a horizontal curve. In order to avoid safety risks caused by communication system errors or information transmission delays, autonomous vehicles have higher requirements on the lateral clearance of curve sections. The calculation results show that under the condition of high design speed, the radius required to satisfy the lateral clearance is much larger than the radius required to satisfy vehicle force balance. According to this conclusion, designers should pay attention to the driving risk caused by the delay in updating the information of on-board sensors when the vehicle speed is fast. Although there is no driver in an autonomous vehicle, passenger comfort cannot be ignored when designing vertical curves. Based on the model calculation and comparison, the radius of a convex vertical curve required for autonomous vehicles is almost half of the current regulations, while the required radius of a concave vertical curve is almost the same. This is because, on the convex vertical curve, the blind spot of an autonomous vehicle's sensor is smaller, and the blind spot of a driver's sight is larger. Because of the advantages of autonomous vehicles, there is a big difference between the recommended value of a convex vertical curve's radius and the current specification. From the calculation results, the concave vertical curve is mainly affected by impact mitigation when the design speed is low. In addition, impact mitigation is affected by the dynamic characteristics of the vehicle. The difference of dynamic characteristics between autonomous vehicles and traditional vehicles is small, so the difference between the recommended radius of a concave vertical curve and the current specification is also small. However, when the design speed is high, the main factor affecting the radius of a concave vertical curve changes from impact mitigation to sight distance requirements. Autonomous vehicles have an even bigger advantage in sight distance. In addition, the minimum value of the radius of a vertical curve can only ensure that vehicles drive relatively smoothly and cannot ensure that passengers have a high degree of comfort. General values are therefore recommended at design time. In order to avoid the waste of land resources, this paper studies lane width and width of the shoulder. With the help of an assisted driving system, autonomous vehicles can effectively reduce the lateral clearance required by vehicle swing. At the same time, with the help of Internet-of-vehicles technology, autonomous vehicles are more suitable for passenger and cargo lane separation. Lanes with different functions can use different lane widths.

The advantages of autonomous vehicles are the early identification of hazards and orderly driving. The ability of autonomous vehicles to identify hazards ahead of time helps designers adopt more aggressive values when designing minimum indicators. More aggressive values help freeways through complex terrain. The ability of orderly driving brought about by the Internet of vehicles helps designers dispose of the limitation of the largest indicators. It is conducive to saving construction costs and land resources.

6. Conclusions

The purpose of this study is to explore and systematically study the design standards and technical indicators of freeways in the fully autonomous driving environment. This paper analyzes the formulation principles and parameter values of some design indicators in the traditional driving environment. At the same time, this paper analyzes the compatibility and adaptability of the corresponding indicators in the autonomous driving environment. This study helps us to improve the geometric design standards of freeways, make them more suitable for the traffic characteristics of autonomous vehicles, and realize the coordination of autonomous vehicles and freeway design.

According to the characteristics of perception, response, and decision making of autonomous vehicles, combined with driving safety, this paper studies the design control factors such as vehicle designs, design speed, and driving sight distance of autonomous-driving highways. Then, based on the requirements of sight distance, driving mode, and passengers' comfort, the recommended values of horizontal, vertical, and cross-section design indexes of an autonomous driving freeway are put forward. The research results will optimize and guide the road alignment design of autonomous driving freeways in the future and make the construction of future freeways more adaptable to autonomous vehicles' operating characteristics and social economic conditions.

The limitation of this study is that it only studies some technical indicators related to psychological and physiological characteristics such as reaction time and vision. The following research needs to continue to analyze other road design indicators controlled by the driver's characteristics and then further test and optimize the values of related indicators through traffic simulation experiments or experimental roads.

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