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Research Article

Theoretical Research on Longitudinal Profile Design of Superhighways

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To improve driving safety on superhighways, longitudinal profile design parameters of a superhighway are calculated via force analysis while a car is driven on a slope. The calculations consider characteristics of drivers, cars, and roads. According to the vehicle type, design speed, and natural conditions, the maximum longitudinal slope of a superhighway is calculated and compared with those of an ordinary superhighway and high-speed railway. Based on analysis of the vehicle climbing performance, braking performance, and driver visual characteristics, the maximum and minimum slope lengths of a superhighway are calculated. By analyzing the elements of vertical curves, the minimum radius and minimum length of the vertical curves of a superhighway are calculated by considering factors such as mitigating the impact at the slope bottom, driving at night, and driving time along vertical curves. Analysis and calculation results show that when the maximum longitudinal slope is 2.50%, 2.25%, and 2.00%, the minimum slope length is 450 m, 400 m, and 350 m, respectively, and the minimum vertical curve length is 145 m, 130 m, and 115 m, respectively, and the superhighway travel requirements can be satisfied at speeds of 180 km/h, 160 km/h, and 140 km/h, respectively.

1. Introduction

In more than 10 countries in Europe, such as France and the Netherlands, the maximum speed limit on highways is 130 km/h [1], and in Texas, USA, the maximum speed limit is 137 km/h (85 mile/h) [2]; in Italy, it is 140 km/h [3], while in Germany, there is no maximum speed limit on some highways [4]. The *Highway Engineering Design Guidelines (Draft)* published in 1951 stipulated for the first time that the maximum design speed of highways in China was 120 km/h, and it has been used ever since [5].

More than 60 years have passed, and the technologies of highway construction and automobile performance have greatly improved in China, and it is possible to construct superhighways with a design speed exceeding 120 km/h. Construction of the first superhighway in China began in 2018, which is the Hang-Shao-Yong Highway, from Hangzhou to Ningbo via Shaoxing, and it will open in 2022

in time for the opening of the Asian Games in Hangzhou. It took only two years after the definition of a superhighway was proposed by the current authors in 2016 [6]. In March 2019, construction of the second superhighway with a special traffic lane for automatic driving started, which is the Jing-Xiong Highway, from Beijing to Xiong'an. The development speed of the superhighway is much higher than expected [7].

At present, the superhighway faces two major problems, safety and economy, especially safety is very important. To improve highway safety and efficiency, we established a speed guidance system via the experimental and simulation methods. The results show that the highway speed guidance system can effectively improve safety and driving conditions [7]. Considering that the speed limit on highways in many countries exceeds 120 km/h, automobile and highway construction technologies in China have attained great progress, and the concept of a superhighway was proposed for the first time by the current authors. In the same paper,

we defined different technical grades of a superhighway and demonstrated the feasibility and necessity of the various grades [6]. Subsequently, we published several papers after conducting in-depth research on superhighway safety, economy, and traffic capacity. The safety of superhighways was demonstrated from three perspectives: automobile technology, highway technology, and foreign experience of superhighway safe operation [8]. To evaluate the economic efficiency of superhighways, we compared the cost of traveling by superhighways with the cost of traveling by bus, train, and airplane. The results show that the cost of traveling by superhighways for a single person is between 0.29 and 0.47 yuan/km, which is less expensive than traveling by busses but more expensive than traveling by trains and airplanes [9]. To study the capacity of superhighways, we compared it with that of an ordinary highway. The results show that optimizing the design speed of a superhighway does not increase the traffic capacity, but special highway lanes for automatic driving vehicles can enhance the design speed and also increase the traffic capacity [10].

Due to our research, scholars began to study superhighways. Chen and Peng aimed at the characteristic advantages and disadvantages, opportunities, and threats due to the external environment of a superhighway during the construction and operation management periods and provided suggestions for the future development of superhighways by using strengths, weaknesses, opportunities, and threats (SWOT) analysis [11]. Zhao et al. proposed stringent safety requirements for superhighways based on an investigation of the most common problems in existing highway horizontal curve design. Starting from meeting safety requirements, they established an obstacle identification model for the geometric analysis of flat curves and calculated the safety limit of the horizontal curve radius of superhighways, which provided the basis for the study of superhighways and their flat curves [12].

There are many studies on highways (expressway and freeway) in China and abroad, especially those related to safety. Chen et al. studied single-vehicle (SV) accidents and multivehicle (MV) accidents in adverse driving conditions, such as inclement weather and/or complex terrain [13]. Feng and Chen. studied the relationship between road traffic accidents and road geometric feature [14]. However, there is almost no separate research on highways with a design speed exceeding 120 km/h. The previous studies related to safety mainly examined driving while fatigued speeding, overloaded driving, brake failures, tire burst, geometric design, and safety facilities. Therefore, in this paper, the geometric design of highways is investigated.

Zhang et al. selected seven countries to conduct a comparative study of highway design parameters to illustrate the similarities and differences. They found that there were many similarities in terms of the fundamental design principles. However, differences were observed as well, such as the vertical radius, grade, and so on. Unexpectedly, the design standards in China were far more stringent than those in the selected countries although the design speeds on the highways in these countries exceeded 120 km/h [15]. Fambro et al. presented a new model for determining stopping sight distance requirements for the geometric design of highways. This model is based on parameters describing the driver and vehicle capabilities that can be validated with field data and can result in safe driving behavior. The recommended values are attainable by most drivers, vehicles, and roadways. This model defines stopping sight distances, sag vertical curve lengths, and lateral clearances that are between the current minimum and desired requirements and exceed the vertical curve lengths, which are shorter than the current minimum requirements [16]. Kang et al. proposed separate computational methods for evaluating fuel efficiency, sight distance deficiencies, and expected accident costs for a given highway alignment, depending on detailed geometric characteristics. A case study was presented to demonstrate the effectiveness of the developed methods [17]. Porter et al. proposed a conservative approach to establish geometric design criteria, which were used to address the ranges of the driver and vehicle, roadway conditions, and capabilities that must be considered in design. They established a relationship between the road geometry and operating speed and studied the degree to which the road geometry influences the driving speed, the influence of the road geometry on safety, and the potential impacts on large vehicles [18]. Castro and De Santos-Berbel examined the use of a geographic information system (GIS) for an integrated analysis, taking into account two accident-related factors: the design consistency (DC) (based on the vehicle speed) and the available sight distance (ASD) (based on visibility). Their results showed that DC and ASD were related to crashes in approximately 4% of the studied cases [19]. Dong et al. studied the effects of highway geometric design features on the frequency of truck-involved crashes. They found that the zero-inflated negative-binomial (ZINB) model has desirable distribution properties to describe the relationship between large truck-involved crashes and geometric design features in terms of a better goodness of fit, more precise parameter estimates, more identified significant factors, and improved prediction accuracy [20].

The studies above have played a role in improving highway safety. However, the longitudinal profile of superhighways was not considered in these studies. Therefore, based on force analysis while operating a vehicle on a slope, in this paper, the maximum longitudinal slope of superhighways is calculated according to the vehicle type, design speed, and natural conditions and compared with the maximum longitudinal slopes of ordinary highways and high-speed railways; based on analysis of the vehicle braking performance and driver visual characteristics, the maximum and minimum slope lengths of superhighways are obtained; based on analysis of elements of vertical curves, the minimum radius and minimum length of vertical curves of superhighways are calculated, taking into account factors such as mitigating the impact, illuminated distance, sight distance, and driving time along vertical curves.

2. Overview of Superhighways

2.1. Background of Superhighways. The construction speed and quality of infrastructure projects such as highways and railways in China have attracted worldwide attention and are

considered construction super projects. By the end of 2018, the total highway length in China had exceeded 140,000 km, thereby ranking first in the world for eight consecutive years and far ahead compared with other countries. The starting length of its high-speed railways was 29,000 km, which accounted for more than 60% of the total length of high-speed railways worldwide.

From 1997 to 2007, the railways in China have experienced six speed increases, and the average speed increased from 48.1 km/h to 70.18 km/h [21]; in 2008, the first high-speed railway from Beijing to Tianjin with a design speed of 350 km/h was opened [22]; in 2006, the first Maglev line in China was launched, with a running speed of 430 km/h [23]. Railways have undergone leapfrog breakthroughs in both length and operation speed.

The total length of the highways in China is also constantly breaking historical records. The starting length is already ranked first in the world, and a number of super-projects have been delivered. For example, of the ten longest sea-crossing bridges in the world, five are in China, and the Hong Kong-Zhuhai-Macao Bridge is the longest [24]. However, the maximum design speed limit on the highways in China has never been optimized, which has remained 120 km/h. It has not changed in 68 years, and there is no relevant research on increasing the speed limit on highways.

The development of high-speed railways in China has provided valuable experience for the construction of superhighways. The safe operation of highways in foreign countries with a design speed limit exceeding 120 km/h has provided confidence for the safe operation of superhighways in China. Therefore, the authors proposed the idea of superhighways.

2.2. The Definition of a Superhighway. A superhighway is designed to be a highway with a design speed higher than 120 km/h. The superhighway is different from an ordinary highway. To ensure the safety of a superhighway, the pavement of a superhighway is flatter, the route is smoother, and the facilities are more comprehensive [25].

Since the definition of a superhighway was established, it has been approved by many professors at various universities, such as Tongji University, Southeast University, and Chang'an University, and has aroused extensive interest from scholars attending the First World Transportation Conference in June 2017. In January 2018, the report entitled "Feasibility Study of Superhighways Based on Expenses" at the Donglin-Tongji Academic Conference resulted in a lively discussion among participating scholars. At present, the Intelligent Network and Transportation Joint Research Institute of the Southeast University-University of Wisconsin is engaged in research on autonomous driving lanes based on vehicle-road collaboration technology and has applied for a number of patents in the United States and China, which provides technical support for the development of superhighways.

2.3. Classification of a Superhighway. While defining a superhighway for the first time, the author also proposed different technical grades of superhighways and the maximum design speed. The proposed technical grades of superhighways are listed in Table 1.

Considering safety and economic problems, after several rounds of expert peer review, the classification speed was considered too high, and so the classification and design speed of superhighways were adjusted. The adjusted technical grades and maximum design speed of superhighways are summarized in Table 2.

While defining different grades of superhighways, the designated vehicle types, construction modes, and expected construction time were proposed for all grades. A comparison of the different superhighway grades is provided in Table 3.

The above vehicle types, construction modes, and expected construction times of all superhighway grades were only preliminary assumptions when the definition of a superhighway was first introduced, and there will be large discrepancies during the actual development. For example, we had expected that superhighways of grade I would be built in 15 years, but it took only two years after first defining superhighways. With the transformation of highway construction from high speed to high quality and the rapid development of automatic driving technology, superhighway construction at all levels will soon become reality.

3. Design of the Longitudinal Gradient of a Superhighway

3.1. Analysis of Vehicle Driving Force

3.1.1. Slope Resistance of a Car. When a car is driven on a slope, the force component of gravity parallel to the road surface is called slope resistance, as shown in Figure 1.

As seen from the figure above, the slope resistance of a car driven on a slope can be calculated with the following equation:

$$p_i = \pm G_a \cdot \sin \alpha, \tag{1}$$

where P_i is the slope resistance, α is the road slope angle, "+" means that the car is driven up the slope and P_i is opposite to the direction of the car, which inhibits driving, and "−" indicates that the car is driven down the slope and P_i is in the same direction as the car, which accelerates the car [26].

The steepness of the longitudinal slope of a highway is usually expressed as slope i, which is the percentage of the vertical height of the slope to its horizontal length. Therefore, slope i can be expressed as the following equation:

$$i = \frac{h}{s} = \tan \alpha. \tag{2}$$

As the slope angle α of the longitudinal slope of a superhighway does not exceed 3°, this value can be substituted in $\tan \alpha$ and $\sin \alpha$. Therefore, the slope resistance can be expressed as the following equation:

$$P_i = \pm G_a \tan \alpha = \pm G_a i. \tag{3}$$

TABLE 1: Novel classification of highways.

Grade	Superhighway									Ordinary highway		
	Grade III			Grade II			Grade I					
Design speed/km/h	240	220	200	200	180	160	160	140	120	120	100	80

TABLE 2: Adjusted classification of highways after peer review.

Grade	Superhighway									Ordinary highway		
	Grade III			Grade II			Grade I					
Design speed/km/h	180	160	140	160	140	120	140	120	100	120	100	80

TABLE 3: Comparison of the different superhighway grades.

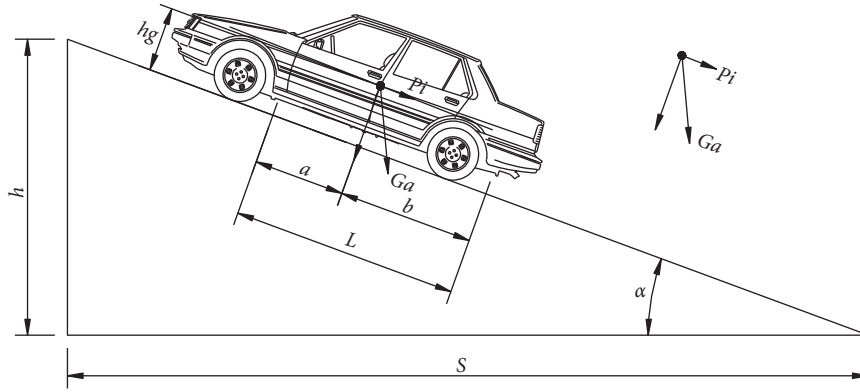| Grade	Vehicle type	Construction mode	Expected construction time
Grade I	Cars and trucks	Retrofitting existing highways	15 years
Grade II	Only for cars	According to passenger-dedicated railway specifications	30 years
Grade III	Only for autonomous vehicles	According to high-speed railways	40–50 years

FIGURE 1: Force analysis while driving on a slope.

3.1.2. Necessary Conditions for Driving. Driving the car on the slope is not only affected by the slope resistance P_i but also by the rolling resistance P_f, air resistance P_w, and inertia resistance P_j.

To enable the car to move forward, the traction force of the car must be equal to the sum of all the resistance forces encountered when the car moves, which is expressed in the following equation:

$$P_t = P_f \pm P_i + P_w \pm P_j. \tag{4}$$

Substituting the previous relevant equation into equation (4), the following equation is then obtained:

$$\frac{M_e \cdot i_k \cdot i_0 \cdot \eta_m}{r_k} = G_a f \pm G_a i + \frac{KFV^2}{13} \pm \delta \frac{G_a}{g} \cdot \frac{dv}{dt}, \tag{5}$$

where "+" before P_i means upslope and "−" means downslope; also, "+" before P_j indicates acceleration and "−" indicates deceleration. P_f and P_w are always positive.

Equations (4) and (5) are called traction balance equations, that is, the traction P_t of the car must be equal to the sum of all the resistance forces. The above conditions are

necessary for the car to move forward, also referred to as the driving conditions.

3.1.3. Sufficient Conditions for Driving. The traction force of a car is the same as the horizontal reaction force of the road exerted on the wheels, and the horizontal reaction force of the road exerted on the wheels is restricted by the adhesion conditions between the tires and the road. If the friction between the tires and the road is very small, it cannot provide enough horizontal traction and the tires will slip on the road surface or idling can even occur. Therefore, the traction force of a car must be lower than or equal to the friction force between the tires and the road; that is, it should be lower than the limiting value of the horizontal reaction force exerted by the road on the tires, which can be expressed as the following equation:

$$P_t \leq G \cdot \phi, \tag{6}$$

where G is the load of the wheels, and for an all-wheel drive car, it is the total weight of the car, while for a rear-wheel drive car, it is lower than the total weight of the car. The value range of regular cars is from 0.5 G_a to 0.65 G_a and that

of heavy vehicles is from 0.65 G_a to 0.8 G_a. In addition, ϕ is the coefficient of friction between a tire and the road.

Equation (6) describes the sufficient condition to drive a vehicle, also known as the adhesion condition. The combination of equations (4) and (5) defines the sufficient and necessary conditions for automobile driving, also known as the driving and adhesion conditions of automobile movement:

$$P_t = P_f \pm P_i + P_w \pm P_j \le G\phi. \tag{7}$$

3.2. Maximum Longitudinal Slope of a Superhighway

3.2.1. The Basis for Determining the Maximum Longitudinal Slope. Vehicle type: The power performance and braking performance of different vehicle types, such as passenger vehicles, cargo vehicles, and other different types of vehicles, are quite different. Therefore, the design requirements on the maximum longitudinal slopes of highways are also different.

Design speed: According to analysis results of the dynamic characteristic curves of vehicles, the climbing ability is inversely proportional to the driving speed. The faster a vehicle is driven, the lower its climbing ability is. Therefore, when determining the maximum longitudinal slope, a certain driving speed must be ensured.

Natural conditions: The altitude, climate, and terrain of the area where the highway is located will also affect the driving conditions and climbing ability of cars.

3.2.2. Formulation Method of the Maximum Longitudinal Slope Standard. When defining the maximum longitudinal slope of a highway, the Highway Engineering Technical Standard mainly considers the climbing ability of vehicles in the upslope direction, the safety of vehicles in the downhill direction, as well as the driving requirements of vehicles in the uphill and downhill directions when roads are slippery due to rain and snowfall.

The maximum longitudinal slopes of highways with different design speeds stipulated in the highway engineering technical standards are listed in Table 4.

In actual highway route design, the primary basis for determining the maximum longitudinal slope is the maximum climbing ability of vehicles, and the maximum climbing ability is mainly determined by calculations, research, and experiments.

The calculation method relies on the dynamic performance diagram of a vehicle. According to the principle of constant-speed climbing, the calculation method is based on the vehicle type, speed, and load when the vehicle is driven in the upslope direction.

The investigation method is aimed at determining the maximum longitudinal slope value by investigating the driving conditions of automobiles on slopes and analyzing survey data of slope sections. The test method selects the design vehicle as the experimental object, drives on different longitudinal slopes at different speeds, and determines the appropriate longitudinal slope according to the parameters of the vehicle speed and slope length of the designed route.

3.2.3. Maximum Longitudinal Slope of Superhighway. For a superhighway, the determination of its maximum longitudinal slope needs to consider the climbing ability of a car in the upslope direction and its stability in the downslope direction. However, these longitudinal slope considerations do not necessarily pertain to livestock vehicles or rain, snow, fog, and other special weather conditions, and special requirements can be achieved by adjusting the speed limit.

The Design Standard for High-speed Railways and the Design Standard for Intercity Railways stipulate that the maximum gradients of the main lines of high-speed and intercity railways shall not be higher than 2.0%. Under difficult conditions, the maximum gradient shall not be higher than 3.0% after technical and economic review. At the same time, the Design Standard for Intercity Railway stipulates that the maximum slope of intercity railway lines shall not be higher than 3.0% and shall not be higher than 3.5% under difficult conditions. The maximum limits of the longitudinal slope specified in railway route design standards are summarized in Table 5.

Therefore, according to the current maximum longitudinal slopes of highways at all levels, as well as the vehicle climbing and braking performance, the maximum longitudinal slope of a superhighway is calculated according to the relevant railway specifications, as listed in Table 6.

As indicated by Tables 4 and 6, when the design speed is 120 km/h and 100 km/h, the maximum longitudinal slope of a superhighway is the same as that of an ordinary superhighway.

3.3. Minimum Longitudinal Slope of a Superhighway

3.3.1. The Basis for Determining the Minimum Longitudinal Slope. To ensure safety and comfort while driving a car at the design speed, it is generally required that the design road slope is as flat as possible. However, in order to ensure that rainwater and slope seepage can be discharged in time and prevent moisture from infiltrating into the roadbed and affecting the stability of the roadbed, a longitudinal slope higher than 0.3% should be established. In actual engineering design, a longitudinal slope higher than 0.5% should generally be adopted.

3.3.2. Minimum Longitudinal Slope of a Superhighway. The design standard of a superhighway is much more stringent than that of an ordinary highway, and its drainage system should be optimal. In the case of an optimal drainage system design such as bridges and tunnels, the minimum longitudinal slope is generally not considered. However, the minimum longitudinal slope in excavated or other sections with poor drainage should be the same as that of an ordinary highway. The longitudinal slope should be higher than 0.3%. If conditions permit, the longitudinal slope should be higher than 0.5% as frequently as possible.

4. Slope Length Limit of a Superhighway

4.1. Minimum Slope Length Limit of a Superhighway. The longitudinal slope length of a highway refers to the distance

TABLE 4: Maximum longitudinal grades of highways.

Design speeds (km/h)	120	100	80	60	40	30	20
Maximum longitudinal slopes (%)	3.00	4.00	5.00	6.00	7.00	8.00	9.00

TABLE 5: Maximum slope of railways (unit: %).

Railway grades		I			II		
		Plains	Hills	Mountains	Plains	Hills	Mountains
Traction types	Electrical motor	0.60	1.20	1.50	0.60	1.50	2.00
	Internal combustion engine	0.60	0.90	1.20	0.60	0.90	1.50

Note. Railways of grade I: passenger train running speeds of 160 km/h, 140 km/h, and 120 km/h; railways of grade II: passenger train running speeds of 120 km/h, 100 km/h, and 80 km/h.

TABLE 6: Maximum slope of superhighways (unit: %).

Design speeds (km/h)	180	160	140	120	100
Maximum slopes (%)	2.00	2.25	2.50	3.00	4.00

between two adjacent slope change points along a longitudinal section. The maximum longitudinal slope length should be limited in order to prevent cars from decelerating too much in the upslope direction and braking from occurring too long in the downslope direction. To ensure that fewer longitudinal changes occur when a vehicle is driven, it is necessary to limit the minimum slope length of a highway. Therefore, the superhighway slope length limit is similar to that of a normal highway slope length, including the minimum and maximum slope length limits.

If there are too many slope change points along a longitudinal section of a superhighway, vertical fluctuations will be frequently observed from the visual point of view, similar to traveling between peaks and valleys. From the perspective of the body sensation of a driver, numerous vehicle undulations will seriously affect driving comfort, and the higher the speed is, the more notable the effect will be felt. The design speed of a superhighway is much higher than that of highways of all current grades; therefore, the minimum slope length needs to be more strictly limited. When the gradient difference is large, vertical fluctuation changes occur frequently, which easily results in a limited visual range and line of sight interruptions, thereby affecting driving safety and comfort. Based on the geometric properties of the longitudinal profile of a superhighway, the length between adjacent slope change points should not be very short, and the shortest distance should be longer than the tangent line of the adjacent vertical curve. Therefore, the longitudinal slope of a superhighway should be defined considering the visibility, comfort, and geometric line continuity.

The Technical Standard for Highway Engineering suggests that the minimum longitudinal slope length should not be shorter than the distance traversed by a car traveling at the design speed for 9–15 seconds. On highways, driving for 9 seconds meets the visual and geometric layout requirements. To satisfy these vision and linear layout requirements on low-speed highways, a longer duration is needed. The Technical Standard for Highway Engineering defines the

minimum slope length of highways as a function of the design speed, as listed in Table 7.

The design codes of high-speed and intercity railways also restrict the minimum slope lengths of railway routes. To reduce the longitudinal slope, increasing the slope length as much as possible is adopted in railway route design. According to the relevant railway design regulations, the slope lengths of railway main lines should be designed as long as possible to reduce the slope. The minimum slope length in railway route design should be calculated and determined according to equation (8) and be a multiple of 50 m. Under general conditions, the length shall not be less than 400 m, while under difficult conditions, the length shall not be shorter than 200 m.

$$L_p = \frac{(\Delta i_1 + \Delta i_2)}{2} \times R_{sh} + (0 \sim 0.4)V, \quad (8)$$

where L_p is the minimum slope length, Δi_1 and Δi_2 are the adjacent slope differences at both ends of the slope section, and V is the design speed, in km/h. The coefficient of V is usually 0.4 under general conditions and 0 under difficult conditions. R_{sh} is the radius of the vertical curve.

According to the calculation method and results provided in the Technical Standard for Highway Engineering and referring to relevant specifications of railway design, the calculation results of the minimum slope length of superhighways are listed in Table 8.

As seen from Tables 7 and 8, when the design speed is 120 km/h and 100 km/h, the minimum slope length limit of the superhighway is the same as that of the ordinary superhighway.

4.2. Maximum Slope Length Limit of a Superhighway. A superhighway slope length that is too short adversely impacts driving safety and comfort, and a slope that is too steep is also bad for driving. The design speed of superhighways is usually higher than 120 km/h. When the longitudinal slope is large, the slope resistance that needs to be overcome by high-speed driving and climbing will increase exponentially, and the engine will operate under a full load. If the slope length is too long, the engine may overheat, affecting the service life of the engine and even causing engine damage. When driving down a long slope, due to the long braking

Table 7: Current minimum length of highway slopes.

Design speed (km/h)	120	100	80	60	40	30	20
Maximum slope (%)	300	250	200	150	120	100	60

Table 8: Minimum lengths of superhighway slopes.

Design speed (km/h)	180	160	140	120	100
Maximum slope (%)	450	400	350	300	250

Table 9: Maximum length of a highway slope (unit: m).

Design speeds (km/h)		120	100	80	60	40	30	20
Longitudinal slope (%)	3	900	1000	1100	1200	—	—	—
	4	700	800	900	1000	1100	1100	1200
	5	—	600	700	800	900	900	1000
	6	—	—	500	600	700	700	800
	7	—	—	—	—	500	500	600
	8	—	—	—	—	300	300	400
	9	—	—	—	—	—	200	300
	10	—	—	—	—	—	—	200

Table 10: Maximum slope length of high-speed railways.

Maximum design slope (%)	1.5	2.0	2.5	3.0
Maximum slope length (m)	10000	6000	4000	3000

Table 11: Maximum slope length (unit: m).

Design speeds (km/h)		180	160	140	120	100
Longitudinal slope (%)	0.5	—	—	—	—	—
	1.0	1000	—	—	—	—
	1.5	900	1000	1100	—	—
	2.0	800	900	1000	1100	1200
	2.5	—	—	900	1000	1100
	3.0	—	—	—	900	1000
	4.0	—	—	—	700	900

times, brake friction plates can become overheated, which easily results in brake failure affecting driving safety.

The service targets of superhighways of grade I include busses and trucks in addition to cars. While they are driving on a slope, their speed differences are obvious. The larger the speed difference is, the greater the impacts on the capacity and safety of superhighways are, and therefore, the longitudinal slope length of a superhighway must be limited.

In China, much investigation and experimental research have been carried out when formulating the limit standard of highway longitudinal slope lengths at all levels. On this basis, the Technical Standard for Highway Engineering stipulates the maximum slope length of highways as a function of the design speed, as listed in Table 9.

Based on D-series high-speed trains, the Design Standard for High-speed Railways has defined the maximum lengths of different design longitudinal slopes, as summarized in Table 10.

According to the highway longitudinal slope length at all levels and the maximum longitudinal slope of superhighways provided in the Technical Standard for Highway Engineering, based on relevant railway design specifications, the maximum slope length of superhighways is calculated and listed in Table 11.

The maximum length of a superhighway mainly considers that vehicles should not decelerate too much when driving upslope, while driving in the downslope direction is much less considered. For example, if fewer trucks are expected on superhighways of grade I, brake failure while driving downslope is handled as is done for ordinary highways. Superhighways of grades II and III are only for cars, and all longitudinal slopes are designed to be lower than 2%. To inhibit acceleration when driving downslope, the vehicle speed should be reduced only by wind and rolling resistance, and the brake system will not fail due to a long braking distance.

5. Vertical Curves of Superhighways

5.1. The Role of the Vertical Curve. The design slope line along the longitudinal profile of a superhighway is composed of many individual lines, which causes vehicles to experience shocks and turbulence. When encountering the long slope section of a convex turning point, the lines of sight of drivers are easily impeded, and when the speed is high, a feeling of weightlessness can be generated at the top of a slope. When encountering a concave turning point, as a result of the action of centrifugal forces, passengers can feel weighted

down and uncomfortable, and the springs below the vehicle chassis may become overloaded at the same time. Therefore, in order to make the longitudinal profile of a superhighway smoother and to ensure the stability, safety, and comfort of drivers, it is necessary to establish smooth vertical curves at longitudinal slope change points along the longitudinal profile and connect adjacent straight slope sections naturally.

The transition point of a vertical curve connected to a convex curve is called a convex vertical curve, and when connected to a concave curve, it is a concave vertical curve. Convex and concave vertical curves are shown in Figure 2.

In the figure, ω is the change slope angle, and its value is equal to the algebraic difference between the longitudinal slopes of two adjacent slope sections. That is, $\omega = i_2 - i_1$, where i_2 and i_1 are the design longitudinal slopes of two adjacent straight-line slope sections (expressed as a decimal), with "+" indicating the uphill direction and "-" the downhill direction. When ω is larger than 0, the vertical curve is concave, and when ω is smaller than 0, the vertical curve is convex.

At the slope top of a superhighway, in order to eliminate the turning line of the longitudinal slope, the line is made rounder, and to ensure an unobstructed line of vision of drivers, a convex vertical curve must be established, as shown in Figure 3.

To make the line smoother and reduce bumps and vibrations, concave vertical curves must be located at the bottom of superhighway slopes.
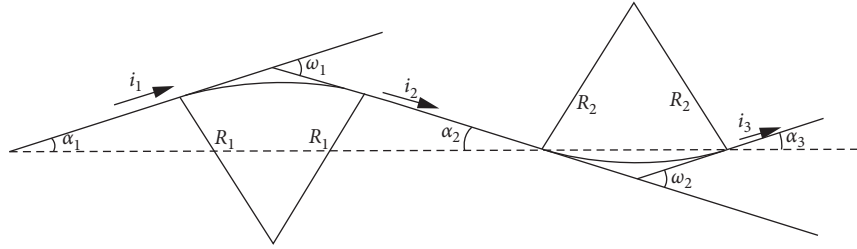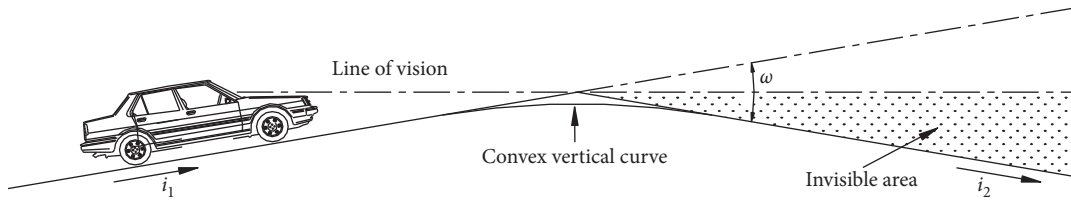
Figure 2: Convex and concave vertical curves.

Figure 3: Convex vertical curve and change slope angle.

5.2. Vertical Curve Element Analysis and Calculation.

In China, the *Highway Route Design Standard (JTG d20-2006)* requires that parabolic or circular curves should be implemented as vertical curves (in Figure 2). At the same time, the standard also specifies that because the slope difference before and after a vertical curve is small, a parabolic curve has a very gentle line shape and its curvature changes little, and its characteristics are almost the same as that of a circular curve. Moreover, a parabolic curve is much more convenient than a circular curve in design and calculation, so it is more common to use a parabolic curve as a vertical curve, as shown in Figure 4.

As shown in Figure 4, in the *xoy* coordinate system, the general equation of a quadratic parabola is the following equation:

$$y = \frac{1}{2k}x^2 + Ax. \tag{9}$$

At any point P on the vertical curve, the slope can be expressed as the following equation:

$$i_p = \frac{dy}{dx} = \frac{x}{k} + A. \tag{10}$$

The radius of curvature at any point on a parabola can be expressed as the following equation:

$$R = \frac{\left[1 + (dy/dx)^2\right]^{(3/2)}}{\left(d^2y/dx^2\right)}, \tag{11}$$

where $(dy/dx) = i$, $(d^2y/dx^2) = (1/k)$, which are substituted into the above equation to obtain the following equation:

$$R = k\left(1 + i^2\right)^{(3/2)}. \tag{12}$$

Since i is between i_1 and i_2 and both i_1 and i_2 are small, i^2 can be omitted, and then $R \approx k$. When $x = 0$, equation the following equation is obtained:
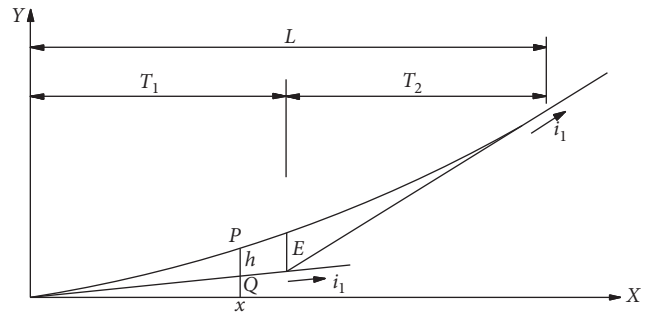

Figure 4: Schematic diagram of vertical curve elements.

$$y = \frac{1}{2R}x^2 + i_1x. \tag{13}$$

When $x = L$ and $i = (L/K) + i_1 = i_2$, equation (14) is yielded.

$$k = \frac{L}{i_2 - i_1} = \frac{L}{\omega}. \tag{14}$$

From equations (12) and (14), $L = R\omega$ is obtained. Because $L = T_1 + T_2$, according to y at the end point of the vertical curve in Figure 4 (at this point $x = L = T_1 + T_2$), the following equation is established:

$$\frac{(T_1 + T_2)^2}{2R} + i_1(T_1 + T_2) = T_1i_1 + T_2i_2. \tag{15}$$

Equation (16) can be obtained by solving equation (15) with $L = T_1 + T_2 = R\omega$ and $T_1 = T_2$.

$$T = \frac{L}{2} = \frac{R\omega}{2}. \tag{16}$$

From $h = PQ = y_P - y_Q = (x^2/2R) + i_1x - i_1x$, the following equation can be derived:

$$h = \frac{x^2}{2R}, \tag{17}$$

where x is the horizontal distance from any point on the vertical curve to the beginning and end points of the vertical curve.

5.3. The Minimum Design Radius and Minimum Design Length of the Vertical Curves of Superhighways.

The Technical Standard for Highway Engineering (JTG B01-2014) and *the Highway Route Design Specification (JTG D20-2006)* restrict the minimum design radius and minimum design length of vertical curves. Because of the different characteristics of vehicles while driving along convex and concave vertical curves and various factors such as vehicle force, vibration, and driver horizon, the design parameters of convex and concave vertical curves are different.

In the longitudinal profile design of a superhighway, the vertical curve is constrained by many factors, among which three main factors determine the minimum radius and length of a vertical curve.

5.3.1. Shock Mitigation.

While a car is driven along a vertical curve, it produces a radial centrifugal force. The centrifugal force along a concave vertical curve is represented as excess weight, and that along a convex vertical curve is represented as weightlessness. When these phenomena of excess weight and weightlessness reached a certain degree, passengers will become uncomfortable. At the same time, this also has adverse effects on the suspension system of the car, especially at the bottom of a concave curve, which may cause damage to the suspension system or a tire blowout. Therefore, in determining the radius of a vertical curve, the centrifugal acceleration must be controlled. The centrifugal acceleration of a vehicle while traveling along a rigid curve can be expressed by the following equation:

$$a = \frac{v^2}{R}\left(\frac{m}{s^2}\right). \tag{18}$$

When v (m/s) is replaced with V (km/h), the following equation is produced:

$$R = \frac{V^2}{13a}\ (m). \tag{19}$$

Experimental results show that the reasonable range of the centrifugal acceleration (a) is from $0.5\,\text{m/s}^2$ to $0.7\,\text{m/s}^2$. However, to further reduce the discomfort caused by shocks and vibrations at the bottom of concave curves and satisfy the requirements of visual smoothness, *the Technical Standard for Highway Engineering (JTG b01-2014)* of China has established the minimum radius of a concave vertical curve accordingly, and the centrifugal acceleration (a) is approximately $0.278\,\text{m/s}^2$, while the calculation is conducted with the following equation:

$$R_{min} = \frac{V^2}{3.6}, \text{ or, } L_{min} = \frac{V^2\omega}{3.6}. \tag{20}$$

5.3.2. Requirements of the Travel Time.

Because the radius of a vertical curve generally is large and the slope angle ω is small, the length of a vertical curve is generally short. When a car transitions from a straight slope to a vertical curve that is too short while driving at a high speed, the driver will have the illusion that the slope changes rapidly and passengers may also feel uncomfortable. Based on the analysis above, in the design of a vertical curve, the shortest driving time along a vertical curve should not be too short. According to experiences in China and abroad, the driving time of a vehicle along a vertical curve cannot be shorter than 3 seconds, and then the shortest length of a vertical curve can be expressed as the following equation:

$$L_{min} = \frac{V}{3.6}t = \frac{V}{1.2}. \tag{21}$$

5.3.3. Requirements of the Sight Distance.

When a car is driven along a convex vertical curve with too small radius, the line of sight of drivers will be blocked by the road on the slope top, thus decreasing the sight distance. When a car is driven along a concave vertical curve with a small radius, there will also be the problem of an insufficient sight distance. At this time, the line of sight of drivers will be blocked by the road at the bottom of the slope and the road of the uphill section ahead. Especially for highways in areas with high topographic relief, in addition to the sight distance problem, when driving at night, the front lights are too close, which seriously affects the driving speed and safety; if there are overpasses, door-type traffic signs and advertisement billboards above a superhighway are located just above a concave vertical curve and they will also affect the line of sight of drivers. Based on the analysis above, the minimum radius and minimum length of vertical curves of superhighways must be limited in consideration of a safe sight distance.

5.4. The Minimum Radius and Length of Convex Vertical Curves of Superhighways.

The minimum length of a convex vertical curve of a superhighway is mainly established to satisfy the requirements of the stopping sight distance. According to the relationship between the length L of a vertical curve and the stopping sight distance S_T, the calculation method is divided into two cases, i.e., $L < S_T$ and $L \geq S_T$.

$L < S_T$ is shown in Figure 5.

If $h_1 = (d_1^2/2R) - (t_1^2/2R)$, then $d_1 = \sqrt{2Rh_1 + t_1^2}$ and if $h_2 = (d_2^2/2R) - (t_2^2/2R)$, then $d_2 = \sqrt{2Rh_2 + t_2^2}$, where R is the radius of the vertical curve (m), h_1 is the height of the sight line of the driver, i.e., the height of the eyes, with $h_1 = 1.2$ m, and h_2 is the height of an obstacle, namely, $h_2 = 0.1$ m. Since $t_1 = d_1 - l = \sqrt{2Rh_1 + t_1^2} - l$, then $t_1 = (Rh_1/l) - (l/2)$.

Since $t_2 = d_2 - (L - l) = \sqrt{2Rh_2 + t_2^2} - (L - l)$, then $t_2 = (Rh_2/L - l) - (L - l/2)$.

Therefore, the sight distance length $S_T = t_1 + L + t_2 = (Rh_1/l) + (L/2) + (Rh_2/L - l)$.

Let $(dS_T/dl) = 0$, and solve the equation to derive $l = (\sqrt{h_1}/(\sqrt{h_1} + \sqrt{h_2}))L$, which is substituted in the above equation to define the following equations:
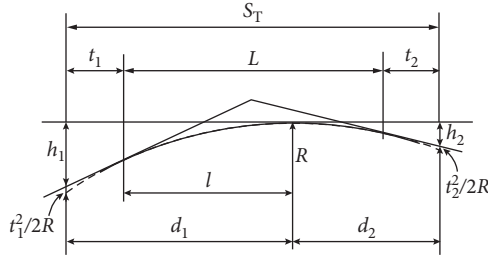
FIGURE 5: Calculation scheme of a convex vertical curve ($L < S_T$).

FIGURE 6: Calculation scheme of convex a vertical curve ($L \geq S_T$).

$$S_T = \frac{R}{L}\left(\sqrt{h_1} + \sqrt{h_2}\right)^2 + \frac{L}{2} = \frac{\left(\sqrt{h_1} + \sqrt{h_2}\right)^2}{\omega} + \frac{L}{2}, \quad (22)$$

$$L_{\min} = 2S_T - \frac{2\left(\sqrt{h_1} + \sqrt{h_2}\right)^2}{\omega} = 2S_T - \frac{4}{\omega}. \quad (23)$$

$L \geq S_T$ is shown in Figure 6.

If $h_1 = (d_1^2/2R)$, then $d_1 = \sqrt{2Rh_1}$. If $h_2 = (d_2^2/2R)$, then $d_2 = \sqrt{2Rh_2}$. According to the method above, equations (24) and (25) are obtained.

$$S_T = d_1 + d_2 = \sqrt{2R}\left(\sqrt{h_1} + \sqrt{h_2}\right), \text{or}, S_T = \sqrt{\frac{2L}{\omega}}\left(\sqrt{h_1} + \sqrt{h_2}\right), \quad (24)$$

$$L_{\min} = \frac{S_T^2 \omega}{2\left(\sqrt{h_1} + \sqrt{h_2}\right)^2} = \frac{S_T^2 \omega}{4}. \quad (25)$$
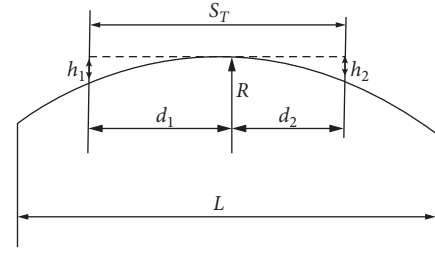
The two situations above are compared.

Let $\Delta L = (S_T^2 \omega/4) - 2S_T + (4/\omega)$, and since $(\omega/4) > 0$, the quadratic parabolic equation for S_T is open upward, and the discriminant is calculated with the following equation:

$$\Delta = (-2)^2 - 4 \times \frac{\omega}{4} \times \left(\frac{4}{\omega}\right) = 4 - 4 = 0. \quad (26)$$

Clearly, $\Delta L \geq 0$, and the result calculated by equation (25) is larger than that by equation (23); hence, equation (25) should be used as an effective control.

According to the three key limit factors, weightlessness at the top of the convex vertical curve, driving time along the vertical curve, and sight distance near the top of the slope, the minimum radius and minimum length of a convex vertical curve can be calculated at different design speeds, as summarized in Table 12.

Table 12 indicates that the general minimum radius stipulated in the technical standards of highway engineering is 1.5~2.0 times the minimum radius limit. The standard also requires that the radius of a vertical curve should be larger than the general minimum radius whenever possible. The minimum length of a vertical curve is equivalent to the distance traversed by a vehicle driving 3 seconds at the design speed at each highway level, which can be calculated with equation (21).

Through the analysis and calculation above, the minimum radius and minimum length of a convex vertical curve of a superhighway are listed in Table 13.

5.5. Headlight Irradiation Distance Requirements. The minimum length of a concave vertical curve of a superhighway must meet the requirements of the lighting and sight distances. First, in order to ensure safe driving at night, headlights should illuminate a long enough distance in front; second, it should be ensured that there is a long enough sight distance for driving under overpass bridges and door-type signs.

According to the relationship between the vertical curve length L and the stopping sight distance S_T, the calculation method of the headlight irradiation distance is also divided into two situations, namely, $L < S_T$ and $L \geq S_T$. $L < S_T$ and is shown in Figure 7.

Since $S_T = L + l$ and $l = S_T - L$, we can obtain the following equation:

$$h + S_T tg\delta = \frac{(L + l)^2}{2R} - \frac{l^2}{2R} = \frac{\omega(2S_T - L)}{2}. \quad (27)$$

This equation is solved to derive the following equation:

$$L_{\min} = 2\left(S_T - \frac{h + S_T \tan\delta}{\omega}\right), \quad (28)$$

where S_T is the stopping sight distance, m; h is the headlight height, with $h = 0.75$ m; and δ is the front light beam diffusion angle, with $\delta = 1.5°$. $L \geq S_T$ is shown in Figure 8.

Equations (29) and (30) can be obtained from Figure 8.

$$h + S_T tg\delta = \frac{S_T^2}{2R} = \frac{S_T^2 \omega}{2L}, \quad (29)$$

$$L_{\min} = \frac{S_T^2 \omega}{2\left(h + S_T tg\delta\right)}. \quad (30)$$

Known data can be substituted into the equation above, and the following equation is generated:

$$L_{\min} = \frac{S_T^2 \omega}{1.5 + 0.0524 S_T}. \quad (31)$$

Similar to the previous calculation method of convex vertical curves, the calculation result of equation (31) is

Table 12: The minimum radius and length of a convex vertical curve of an ordinary highway.

Design speed (km/h)	Stopping sight distance S_T (m)	Impact mitigation $L_{min} = (V^2\omega/3.6)$	Lighting distance $L_{min} = (S_T^2\omega/4)$	Adopted value L_{min}	Value specified in the standard		
					Ultimate minimum radius (m)	General minimum radius (m)	Minimum length of the vertical curve (m)
120	210	4000ω	11025ω	11000ω	11000	17000	100
100	160	2778ω	6400ω	6500ω	6500	10000	85
80	110	1778ω	3025ω	3000ω	3000	4500	70
60	75	1000ω	1406ω	1400ω	1400	2000	50
40	40	444ω	400ω	450ω	450	700	35
30	30	250ω	225ω	250ω	250	400	25
20	20	111ω	100ω	100ω	100	200	20

Table 13: The minimum radius and length of a convex vertical curve of a superhighway.

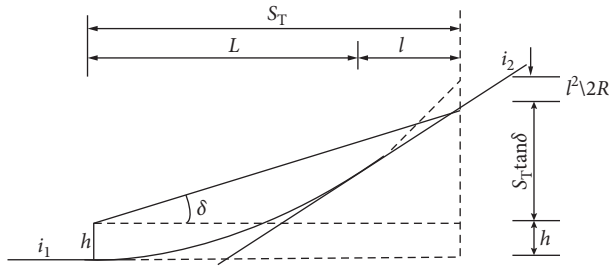| Design speed (km/h)	Stopping sight distance S_T (m)	Impact mitigation $L_{min} = (V^2\omega/3.6)$	Lighting distance $L_{min} = (S_T^2\omega/4)$	Adopted value L_{min}	Recommended value		
					Ultimate minimum radius (m)	General minimum radius (m)	Minimum length of the vertical curve (m)
180	360	9000ω	32400ω	32000ω	20000	31000	145
160	310	7111ω	24025ω	24000ω	17000	26000	130
140	260	5444ω	16900ω	17000ω	14000	21000	115
120	210	4000ω	11025ω	11000ω	11000	17000	100
100	160	2778ω	6400ω	6000ω	6500	10000	85

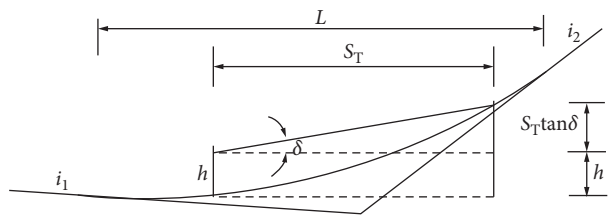Figure 7: Distance of headlight irradiation ($L < S_T$).

Figure 8: Vehicle headlight irradiation distance ($L \geq S_T$).

larger than that of equation (28). Therefore, the calculation result of equation (31) should be taken as the design basis.

5.6. Sight Distance Requirements When There Is an Obstacle above the Concave Vertical Curve. $L \geq S_T$ is shown in Figure 9.

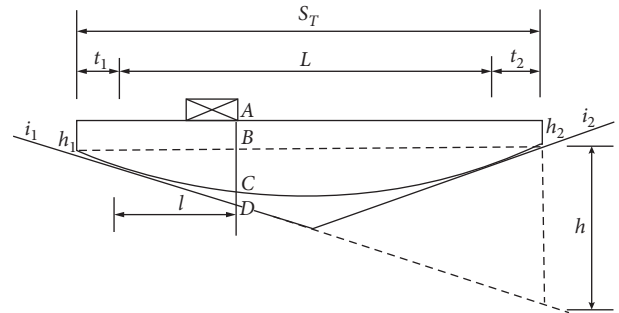Equations (32)–(35) can be obtained by analyzing Figure 9.

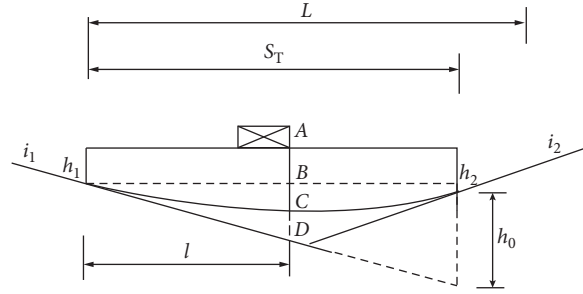Figure 9: Sight distance under an overpass ($L < S_T$).

$$h_0 = \frac{(L + t_2)^2}{2R} - \frac{t_2^2}{2R}, \tag{32}$$

$$AB = h_1 + \frac{h_2 - h_1}{S_T}(t_1 + l), \tag{33}$$

$$BD = h_0\frac{t_1 + l}{S_T} = \left[\frac{(L + t_2)^2}{2R} - \frac{t_2^2}{2R}\right]\frac{t_1 + l}{S_T}, \tag{34}$$

$$CD = \frac{l^2}{2R}. \tag{35}$$

Since $S_T = t_1 + L + t_2$, then $t_2 = S_T - t_1 - L$, and the following equation is yielded:

FIGURE 10: Sight distance under the overpass ($L \geq ST$).

$$h = AB + BD - CD = h_1 + \frac{h_2 - h_1}{S_T}(t_1 + l) + \frac{L(l + t_1)}{2RS_T}(2S_T - 2t_1 - L) - \frac{l^2}{2R}. \tag{36}$$

The condition of $dh/dl = 0$ is used to solve l, which is substituted into the above equation, and after rearrangement, we can produce the following equation:

$$h_{\max} = h_1 + \frac{1}{2RS_T^2}\left[2S_T t_1 + R(h_2 - h_1) + \frac{L}{2}(2S_T - 2t_1 - L)\right] \bullet \left[R(h_2 - h_1) + \frac{L}{2}(2S_T - 2t_1 - L)\right]. \tag{37}$$

The condition of $dh_{\max}/dt_1 = 0$ is used to solve t_1, which is substituted into the above equation; after rearrangement, the following equation is acquired:

$$h_{\max} = h_1 + \frac{[2R(h_2 - h_1) + (2S_T + L)]^2}{8RL(2S_T - L)}. \tag{38}$$

Equation (38) is solved, and we can derive the following equation:

$$h_{\max} = 2S_T - \frac{4h_{\max}}{\omega}\left[1 - \frac{h_2 + h_1}{2h_{\max}} + \sqrt{\left(1 - \frac{h_1}{h_{\max}}\right)\left(1 - \frac{h_2}{h_{\max}}\right)}\right], \tag{39}$$

where $h_{\max}$ is the design clearance under the bridge, with $h_{\max} = 4.5$ m; h_1 is the visual height of the driver, with $h_1 = 1.5$ m; and h_2 is the obstacle height, with $h_2 = 0.75$ m.

Known data can be substituted into equation (39), and equation (40) is obtained.

$$L_{\max} = 2S_T - \frac{26.92}{\omega}, \tag{40}$$

$L \geq S_T$ is shown in Figure 10.

Equations (41)–(45) can be obtained from analysis of Figure 10.

$$h_0 = \frac{S_T^2}{2R}, \tag{41}$$

$$AB = h_1 + \frac{h_2 - h_1}{S_T}l, \tag{42}$$

$$BD = h_0\frac{l}{S_T} = \frac{S_T}{2R}l, \tag{43}$$

$$CD = \frac{l^2}{2R}, \tag{44}$$

$$AC = h = h_1 + \frac{h_2 - h_1}{S_T}l + \frac{S_T}{2R}l - \frac{l^2}{2R}, \tag{45}$$

where $dh/dl = 0$ is used to solve l, which can be substituted into the above equation, and through rearrangement, the following equations are yielded:

$$h_{\max} = h_1 + \frac{1}{2R}\left[\frac{R(h_2 - h_1)}{S_T} + \frac{S_T}{2}\right]^2, \tag{46}$$

$$L_{\min} = \frac{S_T^2\omega}{\left[\sqrt{2(h_{\max} - h_1)} + \sqrt{2(h_{\max} - h_2)}\right]^2}. \tag{47}$$

Known data are substituted into equation (47), and the following equation is derived:

$$L_{\min} = \frac{S_T^2 w}{26.92}. \tag{48}$$

Similar to the previous calculation and comparison method of convex vertical curves, the above two equations should be compared in the same way, and equation (48) should be regarded as the effective control. The minimum radius of a concave vertical curve can be calculated according to the three key limiting factors that affect the design minimum radius of vertical curves of superhighways, and the results are listed in Table 14.

The most unfavourable situation contained in the above table for a concave vertical curve is the impact of radial centrifugal forces. Therefore, equation (48) should be used as

TABLE 14: The minimum radius of a concave vertical curve of an ordinary highway.

Design speed (km/h)	Stopping sight distance S_T (m)	Impact mitigation $L_{\min} = (V^2\omega/3.6)$	Lighting distance $L_{\min} = (S_T^2\omega/(1.5 + 0.0524S_T))$	Sight distance under the bridge $L_{\min} = (S_T^2/26.92)$	Adopted value $L_{\min}$	Value specified in the standard		
						Ultimate minimum radius (m)	General minimum radius (m)	Minimum length of the vertical curve (m)
120	210	4000ω	3527ω	1638ω	4000ω	4000	6000	100
100	160	2778ω	2590ω	951ω	3000ω	3000	4500	85
80	110	1778ω	1666ω	449ω	2000ω	2000	3000	70
60	75	1000ω	1036ω	209ω	1000ω	1000	1500	50
40	40	444ω	445ω	59ω	450ω	450	700	35
30	30	250ω	293ω	33ω	250ω	250	400	25
20	20	111ω	157ω	15ω	100ω	100	200	20

TABLE 15: The minimum radius of a concave vertical curve of a superhighway.

Design speed (km/h)	Stopping sight distance S_T (m)	Impact mitigation $L_{\min} = (V^2\omega/3.6)$	Lighting distance $L_{\min} = (S_T^2\omega/(1.5 + 0.0524S_T))$	Sight distance under the bridge $L_{\min} = (S_T^2/26.92)$	Adopted value $L_{\min}$	Value specified in the standard		
						Ultimate minimum radius (m)	General minimum radius (m)	Minimum length of the vertical curve (m)
180	360	9000ω	6364ω	4814ω	7000	7000	10500	145
160	310	7111ω	5416ω	3570ω	6000	6000	9000	130
140	260	5444ω	4470ω	2511ω	5000	5000	7500	115
120	210	4000ω	3527ω	1638ω	4000	4000	6000	100
100	160	2778ω	2590ω	951ω	3000	3000	4500	85

the effective control. The general minimum radius of ordinary highways stipulated in *the Technical Standards for Highway Engineering* is 1.5~2.0 times the minimum radius. The calculation method of the minimum length of a concave vertical curve is the same as that of a convex vertical curve.

According to the analysis and calculation above, the minimum radius of a concave curve of a superhighway is listed in Table 15.

6. Conclusion

On the basis of conducting force analysis of a car while it is driven, considering the visual characteristics of drivers, vehicle climbing performance, and braking performance, combined with the influence of road design parameters on driving safety and comfort, the design parameters of the longitudinal profile of a superhighway were calculated. Specific conclusions are summarized as follows:

(1) When the design speed is 180 km/h, 160 km/h, and 140 km/h, the maximum longitudinal slope of a superhighway is 2.50%, 2.25%, and 2.00%, respectively, and the minimum longitudinal slope ranges from 0.3% to 0.5%, which can not only satisfy the requirements of the vehicle climbing performance but also the visual requirements of the driver and the requirements of road drainage.

(2) When the design speed is 180 km/h, 160 km/h, and 140 km/h, the minimum slope length of a superhighway is 450 m, 400 m, and 350 m, respectively, and the maximum slope length ranges from 900 m to 1100 m according to the vertical slope, which not only satisfies the vehicle climbing performance requirements but also the braking performance requirements.

(3) When the design speed is 180 km/h, 160 km/h. and 140 km/h, the minimum length of a vertical curve is 145 m, 130 m, and 115 m, respectively, which not only meets the visual range requirements of drivers but also enhances driving comfort.

At present, research on superhighways is still in its infancy in China, and the depth and breadth of research must be improved. We expect that many researchers and engineers will work together to contribute to the development of superhighways in China.

Data Availability

The data used to support the findings of this study are available from corresponding author upon request (e-mail: hymjob@nefu.edu.cn).

Conflicts of Interest

The authors declare that they have no conflicts of interest regarding the publication of this paper.

Acknowledgments

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