Acta Technica 62 (2017), No. 5A, 565–574

Horizontal alignment design theory of superhighways

YONG-MING HE[2], YU-LONG PEI[2,3]

Abstract. The maximum design speed of 120 km/h in China first appeared in the *Highway Engineering Technical Standards (Trial)* in 1951, but vehicle performance, road design and construction technology have been greatly improved for more than 60 years. To meet the development demand of highway design speed above 120 km/h in the future, studied the superhighway alignment design theory. Firstly, defined the definition of the superhighway, determined the classification, and introduced the adaptive roads and motor vehicles. Then, calculated the length limit of a straight line according to driver characteristics and determined the minimum radius of a circular curve on the basis of stress analysis when vehicle is running. Finally, calculated the minimum length of transition curve according to the centrifugal acceleration of vehicle when it is running, the travel time and the passengers' visual characteristics. The calculation and analysis results show that the superhighway linear feature are in line with the vehicle running characteristic, and the superhighway is technically feasible.

Key words. Superhighway, horizontal alignment, circular curve, transition curve, design speed.

1. Introduction

The maximum design speed of 120 km/h in China firstly appeared in the *Highway Engineering Technical Standards (Trial)* in 1951[1], but vehicle performance, road design, and construction technology have been greatly improved since then[2]. The design speed of 120 km/h cannot meet the country's needs, and most other countries have been increasing their highway speed limits[3]. For example, the maximum speed limit is 137 km/h (85 mile/h) inparts of the United States; it is 130 km/h in France, Switzerland, and Austria[4]; it is 150 km/h in Italy[5]; and in parts of the highway in some countries, have not even set a limit[6]· The research related to highway design

[1]Acknowledgement - This paper was supported by the Scientific Frontier and Interdisciplinary Innovation Fund for the Central Universities (2572016CB16) and the National Natural Fund (51638004).

[2]Workshop 1 - Department of Traffic Engineering, Northeast Forestry University, Heilongjiang Harbin150040

[3]Corresponding author: Yu-long PEI

speeds higher than 120 is still lacking in China, and related foreign research is also scant.

With the development of automotive technology and road construction technology, it will become possible to improve the design speed of highways and to construct higher-grade highways in China. In order to meet the development demand for highway design speeds above 120 km/h in the future, the study of superhighway plane linear design theory has great practical significance.

2. Overview of superhighway

2.1. Definition of superhighway

Currently, the highways in China have 120 km/h as the maximum design speed; therefore, a superhighway is defined as one in which the design speed is higher than 120 km/h. The superhighway belongs to the highway category, and it uses higher technical indicators than the *Highway Engineering Technical Standards(JTG B01-2014)* [7].

2.2. Superhighway grade division

According to road use function, design speed, and the definition of a superhighway, the roads are divided into highways and common roads, and then the highways are divided into superhighways and common highways[8].

Among them, common highways and common roads correspond to highways and roads from grades 1–4 in the *Highway Engineering Technical Standards* (JTG B01-2014), and the design speed has not changed. According to the design speed, superhighways are divided into three grades.

Therefore, the new standards of road grade division are shown in Tables 1 and 2.

Table 1. New standards of road grade division

Road grade	**Highway**					**Road**							
	Super highway	**Commonhighway**				**1**		**2**		**3**		**4**	
Design speed (km/h)	>120	120	100	80	60	100	60	80	40	60	30	40	20

Table 2. New standards of superhighway grade division

Highway grade	**Superhighway**									**Common Highway**			
	Grade one			**Grade two**			**Grade three**						
Design speed (km/h)	180	140	120	160	140	120	140	120	100	120	100	80	60

2.3. Comparison of different superhighway levels

According to the classification above, the service objects, construction methods, and years of implementation the different superhighway levels are shown in Table 3.

Table 3. Comparison of different superhighway levels

Super highway	**Service objects**	**Construction methods**	**Years of implementation**
Grade **1**	For passenger vehicles and trucks	Reconstruction of existing highway	15 Years
Grade **2**	Only for passenger vehicles	Construction of electric multiple unit(EMU) line	30 Years
Grade **3**	Only for automatic driving vehicles	Construction of high-speed railway	40–50 Years

3. Superhighway horizontal alignments

3.1. Horizontal alignment

The road is a ribbon of a three-dimensional entity, the space form of the road midline is called the route, and its projection line in the horizontal plane is known as the horizontal alignment of the road [9].

Route design is divided into plane line design, longitudinal section design, and cross-section design. Plane line design is the most important part of superhighway alignment design[10]. Thus, this paper mainly examines the plane linear design theory and its three design elements.

3.2. Three elements of horizontal alignment

There are three kinds of relationships between the steering wheel plane and the body longitudinal axis plane of a vehicle: (1) the angle is 0, (2) the angle is constant, and (3) the angle is variable[11].

According to these three kinds of relationships, the running track lines are as follows:

1. The curvature is zero, and the radius of the running track lines is infinite, so

the line is a straight line, as shown in Fig.1.

Fig. 1. Straight sections

2. The curvature is a constant, and the radius of the running track lines is also a constant, so the line is a circular curve, as shown in Fig. 2.

Fig. 2. Round curve sections

3. The curvature is variable, changing from zero to a constant, and the radius of the running track lines is also variable, changing from infinity to a constant, so the line changes from a straight line to a circular curve, as shown in Fig. 3.

Fig. 3. Easement curve sections

The design elements of the plane lines of superhighways and common roads are the same: straight line, circular curve, and transition curve. It can also be called the three design elements of plane line design. To simplify the design, designers can only use two kinds of elements, the straight line and circular curve, when designing lower-grade roads. There is no uniform regulation restricting the proportion or frequency of use of plane line elements when designing common highways. As long as used reasonably, and each element is configured properly, it can meet users' driving needs. The superhighway plane line elements design must be based on human vision/psychology, the conditions of the terrain, and the technical grade of the road.

4. Restricted lengths of straight line

4.1. Maximum length of straight line

In the design of traditional highways, straight lines are widely used, but in the majority of cases, long straight lines are difficult to coordinate with the terrain. If the length is not used properly, it will not only destroy the continuity of the overall alignment of the road but also fail to achieve the coordination of the alignment design itself.

Long, straight lines often make drivers feel bored and tired. Moreover, it is difficult to accurately visualize the distance between two vehicles, so impatient drivers often pull out of the straight line as soon as possible and then speed up repeatedly, resulting in serious speeding that could easily lead to traffic accidents. Therefore, when using straight lines and determining their length, designers must be cautious and avoid using them for too long.

According to foreign research results, for road design speeds higher than or equal to 60 km/h, the maximum straight line length should be the distance covered while driving for about 70 s at the design speed, which is equivalent to the length of 20 V. The vehicles running on superhighways of grades 1 and 2 are controlled by drivers; therefore, the above factors need to be considered. Superhighways of grade 3 are special roads for self-driving cars, and the maximum length of the straight line is not restricted. The maximum straight line lengths of superhighways are shown in Table 4.

Table 4 Straight line length limit

V(km/h)		Grade 1			Grade 2			Grade 3		
		180	160	140	160	140	120	140	120	100
Maximum(m)		-	-	-	3200	2800	2400	2800	2400	2000
Minimum(m)	Same	1080	960	840	960	840	720	840	720	600
	Reverse	360	320	280	320	280	240	280	240	200

4.2. Minimum straight line length

(1) Minimum length of a straight line between two curves that turn in the same direction

Inserting a short straight line between two curves that turn in the same direction is not reasonable. Visually, it is easy to see the straight line and the two curves at the ends as an illusion of the reverse curve or even see the two sections of the curve as one when it is too short. This design destroys the continuity of the overall alignment of the road and can easily cause driving operation errors. Therefore, the design should be avoided. Because the defect generated by the linear combination can easily make the driver see an illusion, it is necessary to restrict the minimum length of the straight line between the curves at the two ends that turn in the same direction. Then, the adjacent curves ahead cannot be visible to the driver at the same time, so it can avoid the above shortcomings. Given the reasons above, *The Highway Engineering Technical Standards* (JTG B01-2014) and *TheSpecifications for Highway Routes* (JTG D20-2006) recommend that the advisable minimum length (m) between two curves turning in the same direction be not less than six times the design speed (km/h).

The requirements of high-speed (60 km/h or higher) roads should be ensured as far as possible; the design speed of superhighways of grades 1 and 2 is far higher than 120 km/h, and it is controlled by humans, so it must be guaranteed. Superhighways of grade 3 are special highways for self-driving cars, and the minimum length is not restricted. The minimum lengths of straight lines between curves turning in the same direction at the two ends are shown in Table 4.

(2) Minimum length of a straight line between two curves that turn in opposite directions

When two curves that turn in opposite directions have no transition curve, taking into account the need to set the transition section of superelevation and widening as well as the driver's steering operation needs, designers should set the length of the straight line as a widening or superelevation transition section. *TheHighway Engineering Technical Standards* (JTG B01-2014) and *TheSpecifications for Highway Routes* (JTG D20-2006) suggest that the minimum length (m) of a straight line between two curves that turn in opposite directions be not less than two times the driving speed (km/h). Superhighways of grade 3 are special highways for self-driving cars with no minimum length restriction. The minimum lengths of straight lines between curves turning in opposite directions at the two ends are shown in Table 4.

5. Determining the radius of circular curves

5.1. Vehicle horizontal stress analysis when running

When vehicles are running on a circular curve, they are affected by gravity and the centrifugal force. Due to the production of centrifugal force, when vehicles are running on the curve, they are at risk of slipping outward and overturning. However, as modern automobile manufacturing standards minimize the center of gravity of the vehicle, the risk of overturning is very small, and overturning only occurs after a slip, so designers only need to restrict slips .

Fig. 4 shows that the lateral force generated by a vehicle running on a horizontal curve is as follows:

$$Y = C \cdot \cos\beta \pm G_a \cdot \sin\beta$$

Usually, the angleβ is small; then $\cos\beta \approx 1$ $\sin\beta \approx \tan\beta = i_0$

$$Y = C \pm G_a \cdot i_0 \tag{1}$$

where $i_0$is the transverse slope of the road surface, "$\pm$" is "+" or "-", and "-"

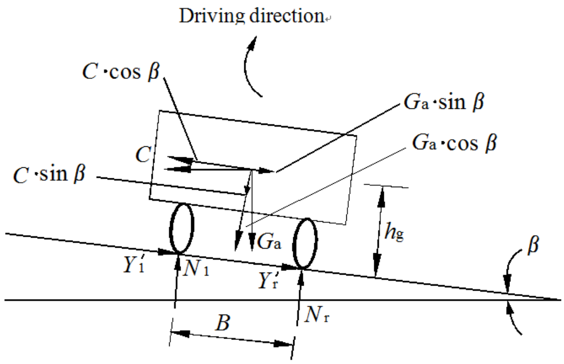

Fig. 4. Force analysis of vehicle while driving on transverse slope

means the component of centrifugal force parallel to the pavement and the gravity of the vehicle are in the same direction (i.e., the vehicle running outside the road does not have a double slope with superelevation). "-" means the opposite of the above (i.e., the vehicle running inside the road does not have a double slope with superelevation).

Centrifugal force C is calculated by

$$C = \frac{G_a}{g} \cdot \frac{v^2}{r} \tag{2}$$

where v is vehicle speed, m / s, g is acceleration due to gravity, m / s2, and R is the road curve radius, m.

By putting Eq. 2 into Eq.1, it have

$$Y = \frac{G_a \cdot v^2}{gR} \pm G_a \cdot i_0 = G_a \left(\frac{v^2}{gR} \pm i_0 \right) \tag{3}$$

The ratio of lateral force Y to vehicle weight G_a is called the lateral force coefficientμ(Wang, Li 2008):

$$\mu = \frac{Y}{G_a} = \frac{v^2}{gR} \pm i_0 \tag{4}$$

A vehicle's lateral stability does not depend on the absolute value of Y, which depends on the relative lateral force per unit mass of the vehicle.

The following can be obtained from the above equation:

$$R = \frac{v^2}{g\left(\mu \pm i_0\right)} \tag{5}$$

Through a stress analysis, it can be deduced that the curve radius value to ensure no slippage is as follows:

$$R = \frac{V^2}{127(\mu \pm i)} \tag{6}$$

Where V is the vehicle speed (km/h), μ is the lateral force coefficient, and i is the road transverse slope, which takes a "+" in Eq. 6 when the vehicle runs inside of the curve and a "-" when it is outside of the curve.

When the superhighway grade is decided and the design speed is a fixed value, then the curve radius R is only related to the lateral force coefficient μ and the transverse slope i.

5.2. General minimum radius of circular curve

Referring to domestic and international experience, puts μ and i from Table 4 into Eq. 6 and took the calculated results with upward integer multiples of 50. Then, the general minimum radii (R_{min}) of superhighways are shown in Table 5.

Table 5. General minimum radii of circular curves

V (km/h)	Grade 1			Grade 2			Grade 3		
	180	160	140	160	140	120	140	120	100
u(%)	4	4	5	4	5	5	5	5	5
i(%)	5	5	6	5	6	6	6	6	6
R_{min}(m)	2350	1850	1450	1850	1450	1050	1450	1000	700

Note: The results take 50 integer times.

The above calculation results considered passenger comfort and safety while running the vehicle on the curve at or close to the design speed, and the engineer quantities were not increased too much under complicated terrain conditions (JTG , 2014).

5.3. Circular curve limited minimum radii

According to Eq. 6, when the lateral force coefficient μ and the road cross slope i take the maximum values, and to ensure that the vehicle does not sideslip, then

$$R_{\min} = \frac{V^2}{127(\mu_{\max} \pm i_{\max})} \tag{7}$$

Where V is the design speed (km/h), $\mu_{max}$is the maximum allowable lateral force coefficient, and $i_{max}$is the highest superelevation rate.

According to the existing design technical standards, considering passenger comfort and safety, the maximum lateral force coefficient and superelevation values are shown in Table 5. Then, the results calculated use Eq. 6 and the values are shown in Table 6.

Table 6. Limited minimum radii of circular curves

V(km/h)		Grade 1			Grade 2			Grade 3		
		180	160	140	160	140	120	140	120	100
u(%)		8	8	10	8	10	10	10	10	10
R(m)	i=0.06	1850	1450	1000	1450	1000	750	1000	750	450
	i =0.08	1600	1300	900	1300	900	650	900	650	400
	i=0.10	1450	1150	800	1150	800	600	800	600	400

Note: The results take 50 integer times.

5.4. Minimum radius without superelevation

When the circular curve radius is larger than a certain value, it may not set superelevation at the curve sections, and it allows designers to make the crown slope the same as the straight sections. Considering driving comfort, designers should minimize the lateral force coefficient. According to *TheSpecifications for Highway Routes* (JTG D20-2006), the lateral force coefficient value should range from 0.035 to 0.050.

Because there is no superelevation, the road cross-section is a crown slope. According to the stress analysis, a vehicle running on the outside of the curve is in the worst case. Then, the crown slope $i = i_0$, so according to Eq. 6, it can be obtained as follows:

$$R_{\min no} = \frac{V^2}{127(\mu \pm i)} \tag{8}$$

Where R_{minno} is the minimum radius while there is no superelevation (unit: m), and i_0 is the crown slope whose value ranges from 0.015 to 0.025.

According to Eq. 8, the calculated minimum radii are shown in Table 7.

Table 7. Minimum radii without superelevation

V (km/h)		Grade 1			Grade 2			Grade 3		
		180	160	140	160	140	120	140	120	100
u(%)		4.5	4.5	5.0	4.5	5.0	5.0	5.0	5.0	5.0
R_{min}/ (m)	i_0=1.5(%)	4650	3150	2400	3150	2400	1750	2400	1750	1150
	i_0=2.0(%)	4300	2900	2250	2900	2250	1650	2250	1650	1050
	i_0=2.5(%)	3950	2700	2100	2700	2100	1550	2100	1550	1000

Note: The results take 50 integer times.

6. Conclusions

(1) This paper introduced the concept and the grades of superhighways, analyzed the road and vehicle performance for superhighways of different grades, and put forward the construction methods and implementation periods for each grade of superhighway.

(2) It also described horizontal alignment and the relevant factors to be considered (i.e., the three elements of horizontal alignment).

(3) According to drivers' physiological and psychological characteristics, calculated the length limits of straight lines of superhighways of grades 1 and 2. In addition, we pointed out that for superhighways of grade 3, special roads only for automatic driving vehicles, the maximum and minimum lengths of the straight lines are not restricted.

(4) Ceduced and calculated the general minimum radius, limited minimum radius, and minimum radius without superelevation of superhighways based on a stress analysis while the vehicle is running.

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Received November 16, 2017