Applied Mathematics & Information Sciences
An International Journal

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Research on Vehicle Swing Model based on Road Structure: Driving Safety and Comfort

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Received: 20 Jun. 2012; Revised 11 Oct. 2012; Accepted 13 Nov. 2012
Published online: 1 Mar. 2013

Abstract: The vehicle swing is a major factor on driving safety and comfort, while the acceleration noise is exactly a description of vehicle swing. Thus, acceleration noise can be a good evaluation indicator of driving safety and comfort. First, the vehicle forces are analyzed in three dimensions, and six vehicle swing models (VSMs) are established based on different road structure by combining acceleration noise theory. Then, the time discrete method is used to further discretize these models for easy calculation and application in practice projects. Finally, a large number of simulation experiments are performed with appropriate roads. The simulation results show that curvature radius, ramp angle, and superelevation slope angle are the major influence factors to driving safety and comfort. This paper not only provides mathematic expression in driving safety and comfort evaluation, but also has certain reference to the geometric design during the design of new highway.

Keywords: Acceleration noise, vehicle swing model, time discrete method, road structure, driving safety and comfort

1. Introduction

Nowadays, traffic safety is an important social and economic problem. According to the European Road Safety Observatory Report [1], over than 1, 000, 000 accidents, with around 40, 000 fatalities in 2006. A major cause is the rapid increase in the number of vehicles, causing more traffic accidents and fatalities year by year. Thus, research on driving safety has been the focus that people pay attention to. And some research institutes have made some contribution to improvement of driving safety and comfort.

In the earlier study, most researchers analyzed the causes of traffic accidents based on a large number of accidents, and obtained some simple relations between accidents and influencing factors. However, they studied based on accidents that are already happened and took remedial measures later. In recent years, some people are becoming more and more concern about impact of road factors on traffic safety. For instance, Fan [2] established the multistage fuzzy comprehensive evaluation model and applied it in safety assessment of highway based on grey correlation method. Pan [3] firstly analyzed some important factors of influence road traffic safety, including driver, road structure, weather, and then presented an evaluation of road traffic safety by using the gray cluster and neural network. In addition, some researchers [4-5] analyzed different road alignments in a horizontal plane, such as circular curve, transition curve and so on. They established some useful models, and made much analysis to driving safety and comfort. However, most methods didn't have the quantitative mathematics model and comprehensive study. Other improved methods are mainly aiming at existing roads, they will make some reconstruction to roads if some problems are discovered, which causes additional cost.

According to traffic flow theory, the acceleration noise (AN) is a description of vehicle swing and regarded as a quantitative evaluation indicator of driving safety and comfort [6-7]. Jones and Potts [6] did a lot of measurements by means of TC08F model tachograph mounted on a test vehicle. They draw a conclusion that acceleration noise is a very useful traffic parameter being compared in different highways, drivers, and road condition. Some studies have argued that AN is affected by three main factors: driver, road structure, and traffic condition. Among these factors, road structure is very crucial to driving safety and comfort. Thus, this thesis analyzes the vehicle force

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and motion situations in different road structure, and establishes six VSMs. These models are discretized in order to calculate and apply in practice on actual projects, which are in order to improve driving safety and comfort.

2. Acceleration Noise

The concept of AN was proposed by Herman in conjunction with car-following studies [7], and was further used to analyze the quality of driving under various conditions. This parameter denoted by σ, is defined as the root-mean-square deviation of the acceleration of a vehicle in a traffic stream, so that,

$$\sigma = \left\{ (1/T) \int_0^T [a(t) - \bar{a}]^2 dt \right\}^{1/2}. \quad (1)$$

Where T is the effectively running time, $a(t)$ is acceleration of t, $\bar{a}$is the average acceleration.

Some research [5-7] show that the case "$\sigma > 1.5ft/s^2$" means that driving safety and comfort is poor. The case "$\sigma < 0.7$ ft/s^2" indicates that driving safety and comfort is good. The more the number of acceleration is, the worse driving safety and comfort will become. Thus, the AN is chose as a quantitative evaluation indicator of driving safety and comfort, which is reasonable.

3. Vehicle Swing Model

As we know, every vehicle runs in three dimensional space, thus this paper analyzed vehicle forces and motion from the three dimensional angle, as shown in Fig. 1.

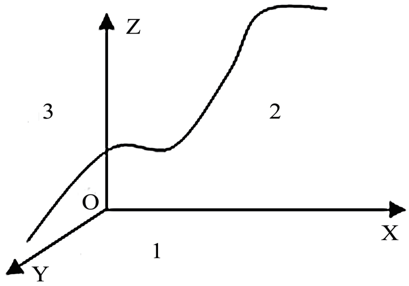

Figure. 1 Sketch map of vehicle's three-dimensional track

The number 1 denotes the horizontal section, the number 2 denotes the vertical section, and the number 3 denotes the cross section. The symbol σ denotes the total AN, and other three components are respectively: σ_1, σ_2, σ_3.

$$\sigma = \sqrt{\sigma_1^2 + \sigma_2^2 + \sigma_3^2}. \quad (2)$$

3.1. Horizontal section

When a vehicle drives on the horizontal plane, its total acceleration a can be divided into two components, the tangential acceleration a_t and the normal acceleration a_n. The tangential acceleration describes changing rate of velocity, and its direction is the same as tangential to the trajectory. The normal acceleration is used to change the direction of the velocity, and its direction points toward the center of circle.

In the design of modern highway plane line shape, there usually are three road alignments: straight line, circular curve, and transition curve [8]. They are called three elements of horizontal alignment. This paper will analyze vehicle state of motion from three kinds of road alignments.

(A) Straight line segment

As one of three elements of plan alignment, the straight line is widely available in highway and urban road. The tangential acceleration is obtained from first derivative of velocity, and normal acceleration is nearly zero in the straight line segment. Thus, VSM can be described as,

$$\sigma = \left\{ (1/T) \int_0^T \left[\dot{V}(t) - (1/T) \int_0^T \dot{V}(t) dt \right]^2 dt \right\}^{1/2}. \quad (3)$$

Where $V(t)$ is the vehicle velocity, and it is represented as functions of time.

(B) Circular curve segment

The circular curve is a common component of curve on the road. When a vehicle drives on circular curve, its stability will be affected by the centrifugal force. The magnitude of force is mainly affected by the curve radius. When a vehicle drives on circular curve of radius is R. The acceleration can be obtained easily based on forces analysis. Thus, VSM is represented by,

$$\sigma = \left\{ \frac{1}{T} \int_0^T \left[\sqrt{\dot{V}(t)^2 + (\frac{V(t)^2}{R})^2} - \frac{1}{T} \int_0^T \sqrt{\dot{V}(t)^2 + (\frac{V(t)^2}{R})^2 dt} \right]^2 dt \right\}^{1/2}. \quad (4)$$

(C) Transition curve segment

Transition curve is a kind of curve with curvature continuously changing, and is situated between straight line and circular curve or between two different circular curves. On the urban road, spiral curve is always adopted as the transition curve, and the mathematical expression is $rl = A^2$. Here, r is the curvature radius of a point on spiral curve, l is the length between any point and the starting point of curve, A is spiral curve parameter. Supposing a vehicle starts from origin of transition curve, thus the length that it travels can be got easily. Therefore, VSM is given

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by,

$$\sigma=\left\{\frac{1}{T}\int_0^T\left[\sqrt{\dot V(t)^2+(V(t)^2\int_0^t V(t)dt/A^2)^2}\right.\right.$$
$$\left.\left.-\frac{1}{T}\int_0^T\sqrt{\dot V(t)^2+(V(t)^2\int_0^t V(t)dt/A^2)^2dt}\right]^2dt\right\}^{1/2}. \tag{5}$$

3.2. Vertical section

Any road can not be smooth, so the force situation and state change of vehicle in vertical section should be analyzed. According to the design of road vertical structure, there are two different situations, slope section and vertical curve section.

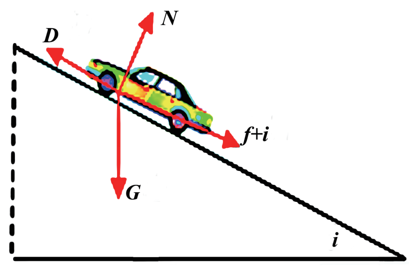

Figure. 2 Vehicle forces on the slope section

(A) Slope segment

The vertical acceleration is caused by vehicle motion on the vertical section of road, and its direction is the same with the advance direction of vehicle. As shown in Fig. 2, the vertical acceleration is given by [8],

$$a(t)=dV(t)/dt=\lambda g(D-f-i)/\delta. \tag{6}$$

Where λ is elevation correction factor, g is gravitational acceleration, δ is coefficient of inertia force, D is vehicle momentum factor, f is coefficient of rolling resistance, i is longitudinal grade (it is positive in the uphill road, and negative in the downhill road). According to reference [8], the expression of D is,

$$\begin{cases} D=(T-R_w)/G \\ T=UM\gamma\eta_T/r \\ R_w=KAV(t)^2/21.25 \end{cases} \tag{7}$$

Where T is vehicle tractive force, R_w is air resistance, U is load rate, M is torque of engine crankshaft, $\gamma$is gear ratio, η_T is mechanical efficiency, r is radius of wheel, K is coefficient of air resistance, A is automotive frontal area, that is projected area of automobile driving direction. Therefore, combining with Eq. 6 and Eq. 7, VSM can be established, that is,

$$\sigma=$$
$$\left\{\frac{1}{T}\int_0^T\left[\frac{\lambda g}{\delta}\left(\frac{UM\gamma\eta_T}{rG}-\frac{KAV(t)^2}{21.15G}-f-i\right)-\bar a\right]^2dt\right\}^{1/2}. \tag{8}$$

$$\bar a=\frac{1}{T}\int_0^T\frac{\lambda g}{\delta}\left[U\frac{M\gamma\eta_T}{rG}-\frac{KAV(t)^2}{21.15G}-f-i\right]dt. \tag{9}$$

(B) Vertical curve segment

There usually be a transitional gradient in the turn of two grade section. And it uses a parabola or a circular curve as the vertical curve expression for convenient calculation in the design of road [8]. The equation of parabola can be represented by,

$$y=x^2/2k+ix. \tag{10}$$

It can be seen from Eq. 10, longitudinal grade of any point on the vertical curve is changing, and the slope of any point on the curve is,

$$i=dy/dx=x/k+i_1. \tag{11}$$

The curve radius of any point on parabola is,

$$R=[1+(dy/dv)^2]^{3/2}\Big/\frac{d^2y}{dx^2}. \tag{12}$$

When a vehicle runs on the vertical curve, it will be affected by a centrifugal force. The direction is the same with gravity in the concave of the vertical curve, and is opposite with gravity in the convex of the curve. When these two forces come to a level, the driver and passengers will be uncomfortable. If even worse, that will affect the drive safety. The force analysis on the vertical section of curve is as shown in Fig. 3.

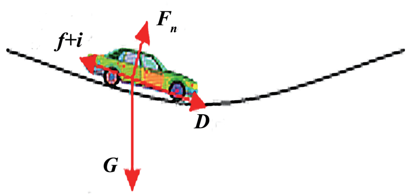

Figure. 3 Vehicle forces on the vertical curve

From the Fig. 3, the centrifugal acceleration of vehicle is represented by,

$$a_n=v(t)^2/R=V(t)^2/12.96R. \tag{13}$$

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The expression of tangential acceleration has some differences with Eq. 6 because of centrifugal force, (when the grade is concave, it will be positive sign in the following formula. Otherwise, it will be negative sign) as following,

$$i = dy/dx = i_1 \pm x/R. \tag{14}$$

So, the resultant acceleration is given by,

$$a = \sqrt{\left[\frac{V(t)^2}{12.96R}\right]^2 + \left\{\frac{\lambda g}{\delta}\left[D - f - \left(i \pm \frac{x}{R}\right)\right]\right\}^2}. \tag{15}$$

Therefore, combining with above ten equations, VSM of vertical curve segment is calculated as,

$$\sigma = \left\{\frac{1}{T}\int_0^T \left[\sqrt{\left[\frac{V(t)^2}{12.96R}\right]^2 + \left\{\frac{\lambda g}{\delta}\left[\frac{UM\gamma\eta_T}{rG} - \frac{KAV(t)^2}{21.15G} - f - \left(i \pm \frac{x}{R}\right)\right]\right\}^2} - \bar{a}\right]^2 dt\right\}^{1/2}. \tag{16}$$

3.3. Cross section

There are two types in cross section of road: the plane section and the superelevation slope section. Lateral acceleration is zero on plane section, so the superelevation slope section is only considered. Usually, there will be superelevation setting on road curve, which offsets centrifugal force for improving driving stability [9-13]. As shown in Fig. 4, when a vehicle runs on curve, it will be affected by the combined action of centrifugal and centripetal force [11], as shown in Fig. 4, the centrifugal and centripetal force can be respectively represented by,

$$F_n = mg\tan\alpha \approx mg\sin\alpha. \tag{17}$$

$$F_r = mv^2/R. \tag{18}$$

Where m is the vehicle weight, g is gravitational acceleration, a is the angle of gradient, its range value is 1.0%˜4.0%, R is the radius of road curve.

Combining with Eq. 17 and Eq. 18, the vehicle lateral acceleration can be represented by,

$$a_h = (V(t)^2\cos\alpha/R - g\sin\alpha). \tag{19}$$

Thus, by using the above equations, VSM on superelevation slope section can be described as,

$$\sigma = \left\{(1/T)\int_0^T \left[\left(\frac{V(t)^2}{R}\cos\alpha - g\sin\alpha\right) - \bar{a}\right]^2 dt\right\}^{1/2}. \tag{20}$$

4. Discrete Treatment

The proposed models above are too complicated, difficult to calculate and apply in practice. Thus, the simplified models are further deduced for easy calculation and application by the time discrete method. Taking time interval Δt as observe time of acceleration, and then the calculation formula will be expressed as,

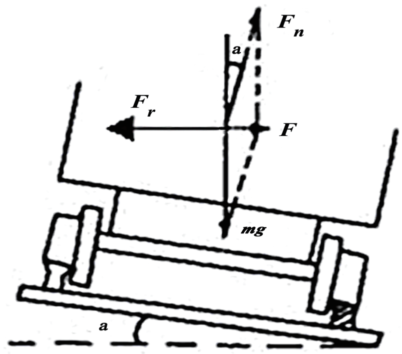

Figure. 4 Vehicle forces on the cross section

$$\sigma = \left\{(1/T)\sum[a_i - \bar{a}]^2\Delta t\right\}^{1/2}. \tag{21}$$

Where a_i is acceleration of the ith time phase, $\Delta t$is equal time interval. Thus, the discrete formula of AN can be given by,

$$\sigma = \left\{\frac{\Delta t(T-\Delta t)}{T^2}\sum a_i^2\right\}^{1/2}. \tag{22}$$

4.1. Horizontal discretization model

Substituting from Eq. 3, 4, 5 into Eq. 22, three discrete vehicle swing models (DVSMs) on the horizontal plane can be described as follows.

Straight line segment:

$$\sigma = \left\{\Delta t(T-\Delta t)/T^2\sum(\dot{V}(t))^2\right\}^{1/2}. \tag{23}$$

Circular curve segment:

$$\sigma = \left\{\frac{\Delta t(T-\Delta t)}{T^2}\sum\left[(\dot{V}(t))^2 + \left(\frac{V(t)^2}{R}\right)^2\right]\right\}^{1/2}. \tag{24}$$

Transition curve segment:

$$\sigma = \left\{\frac{\Delta t(T-\Delta t)}{T^2}\sum\left[\dot{V}(t)^2 + \left(\frac{V(t)^2\int_0^t V(t)dt}{A^2}\right)^2\right]\right\}^{1/2}. \tag{25}$$

4.2. Vertical discretization model

Substituting from Eq. 8, 16 into Eq. 22, two discrete models can be described as follows.

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Slope segment:

$$\sigma = \left\{ \frac{\Delta t(T-\Delta t)}{T^2} \sum \left[\frac{\lambda g}{\delta} \left(\frac{UM\gamma\eta_T}{rG} - \frac{KAV(t)^2}{21.15G} - f - i \right) \right]^2 \right\}^{1/2}. \quad (26)$$

Vertical curve segment:

$$\sigma = \left\{ \frac{\Delta t(T-\Delta t)}{T^2} \sum \left[\frac{V(t)^2}{12.96R} \right]^2 + \left[\frac{\lambda g}{\delta} \left(U\frac{M\gamma\eta_T}{rG} - \frac{KAV(t)^2}{21.15G} - f - \left(i \pm \frac{x}{R} \right) \right) \right]^2 \right\}^{1/2}. \quad (27)$$

4.3. Cross discretization model

Substituting from Eq. 20 into Eq. 22, the discrete model can be described as follow.

Superelevation slope segment:

$$\sigma = \left\{ \frac{\Delta t(T-\Delta t)}{T^2} \sum \left[\left(\frac{V(t)^2}{R} \cos\alpha - g\sin\alpha \right) \right]^2 \right\}^{1/2}. \quad (28)$$

5. Experiments

5.1. Driving safety and comfort on horizontal plane

This thesis chooses 30 seconds for the observation time, driving safety and riding comfort in three road alignments is analyzed respectively. The speed of test vehicle is $V(t) = 12 + \sin(\pi t/3)$ m/s, and circle radius is 225 m, the spiral parameters of transition curve is 450.

The changing of AN value with time is shown in Fig. 5. As we can see from three curves in Fig. 5, the biggest AN value appears in the circular curve, and the driving safety and comfort are the poorest. The straight line segment is the best and has the best driving safety and comfort.

In the line segment, driving stability of vehicle is mainly affected by the driver. However, drive stability is also affected by the road structure in the gentle curve segment and the circular curve, e.g., the curve radius. Thus, different simulation experiments are implemented for different radius. The change situation of AN is shown in Fig. 6. As we can see that AN value decreases with the radius increasing, so the driving safety and riding comfort of vehicle is inversely proportional to curve radius. When the curve radius is more than 600 m, the AN value does not change with different radius and is almost the same as that of the line segment through simulation. Thus, the curve of with large radius can be approximately dealt with the line.

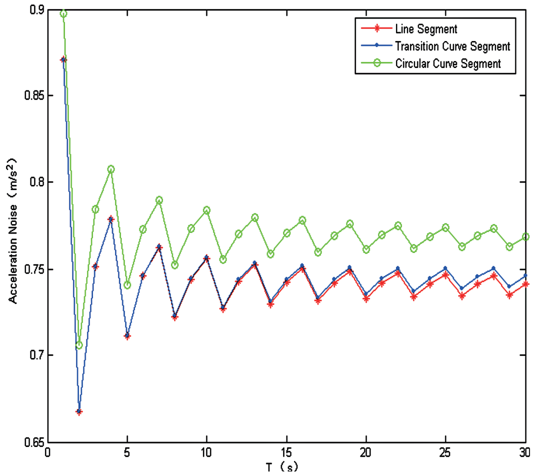

Figure. 5 AN value in horizontal plane

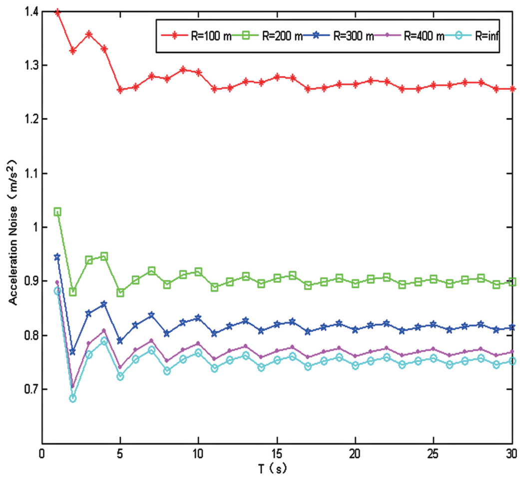

Figure. 6 AN value in different curve radius

5.2. Driving safety and comfort on vertical section

A test vehicle drives on a road with rolling damping coefficient is 0.01. In order to better describe the volatility of speed, observing time is 60s. $\Delta t$is 1s and gravity acceleration is taken for 9.8 m/s^2. According to the rules of sea level elevation, when the sea level elevation is 0 m, the elevation is$\lambda = 1$. The load rate U is 0.9. The sedan car is selected as test vehicle, and its technology parameters are listed in Table 1.

(A) Influence of slope angle

The test vehicle starts with the speed of 60km/h on the vertical slope section. The changing of longitudinal AN with time is revealed to different slopes of road, based on VSM on the ramp, as shown in Fig. 7. The road longitudinal slope angle has a great influence on the driving safety

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Table 1 Technology Parameters of vehicle

Options	Abbreviation	Data
Wheel radius (m)	*r*	0.287
Engine crankshaft torque (N•M)	*M*	0.909
Windward acreage (m^2)	*A*	1.898
Total speed ratio		4.111
Vehicle gravity (N)	*G*	14308
Inertia force coefficient		1.090
Air resistance coefficient	*K*	0.3929

and comfort. When other road conditions are the same, the bigger longitudinal slope angle is, the worse the driving safety and comfort is. A conclusion is obtained that the slope angle should not be set too large, not exceed 0.11 for the sake of security through many simulation experiments.

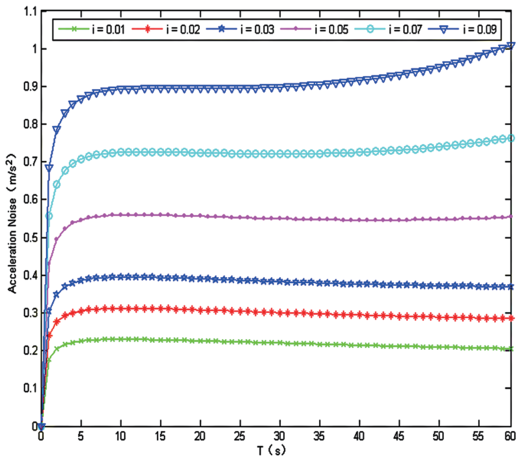

Figure. 7 AN value in different slopes

(B) Influence of vertical curve radius

The test vehicle with initial velocity of 30 km/h runs on vertical curve with slope angle is 0.02. The value of AN in different vertical curve radius is shown in Fig. 8. With the radius increasing, the AN value reduces, which means that the driving safety and comfort will become better.

5.3. Driving safety and comfort on cross section

A test vehicle runs at the speed of 38 km/h on asphalt concrete road, the road curve radius is 480 m. The technology parameters of the vehicle are listed in Table 1. Respectively take high slope angle as: 1.5%, 1.8% and 2.0%, the changing curve of AN value with time is obtained based on cross-sectional model, as shown in Fig. 9.

As shown in Fig. 9, three curves are rising with time. Comparing the changes trend of three curves, the high slope angle is more appropriate to be set for 1.8% when the curve radius is 480m. Too small or too large of the slope angles will be not good for driving safety and comfort, that is to say the high slope angle should be set appropriately based on the curvature radius.

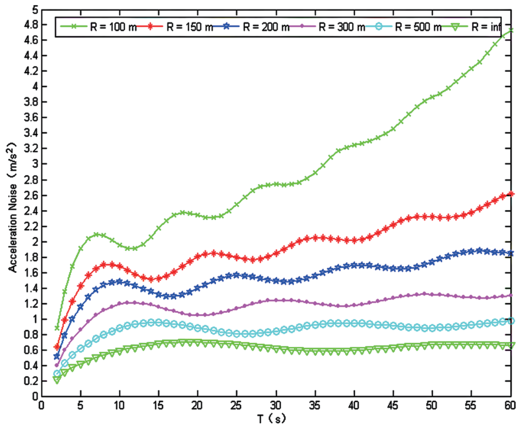

Figure. 8 AN value in different vertical curve radius

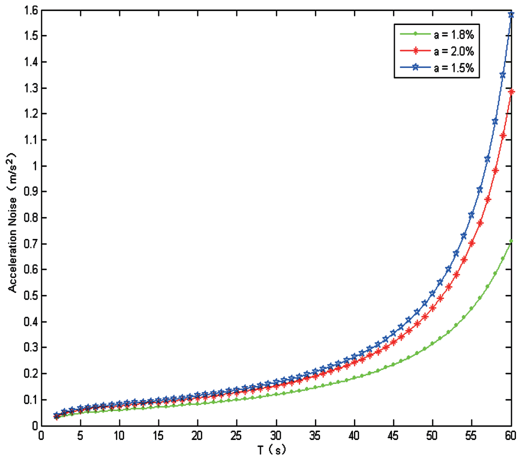

Figure. 9 AN value in different superelevation angle

6. Conclusion

In this thesis, six vehicle swing models are proposed, according to analysis of vehicle forces situation and acceleration changing in various road structures. In order to calculate conveniently and program easily, all discrete models are deduced by using time discrete method. By comparing and analyzing experiment results, some conclusions are put forward as follows.

(1) In horizontal section, driving safety and comfort of vehicle is mainly affected by road structure apart from influence of driver. It is the worst on circular curve, and

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the best on straight segment. However, three kinds of plane alignment are necessary in the design of road. The curve radius must not be too small for security, because driving safety and comfort is roughly proportional to curve radius. The design of plane circle curve can refer to Fig. 6.

(2) In longitudinal section, the gradient angle and curvature radius have greater effect on vehicle swing. Under the same road conditions, the driving safety and comfort will get worse by increasing of the gradient. However, the curve radius has the opposite influence. The road slope should not be set exceed 0.11 for driving security.

(3) In lateral section, it is very important to set the super elevation reasonably. Too big or too small will make driving safety and comfort poor. In a word, the super slope angle should be set based on the road curvature radius.

The VSMs in this paper not only provides support for driving safety and comfort evaluation and improvement, but also has certain parameters for reference to ensure road quality. The follow-up research will focus on further subdividing road structure classification. More various VSMs will be established based on analysis to complex sections, combined with all kinds of road structures.

Acknowledgements

This study was supported by the Natural Science Foundation of JiangXi, China (010GQS0076), by Science and Technology Project of Jiangxi, China (GJJ09254).

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