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Research Article

A New Model of Stopping Sight Distance of Curve Braking Based on Vehicle Dynamics

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Compared with straight-line braking, cornering brake has longer braking distance and poorer stability. Therefore, drivers are more prone to making mistakes. The braking process and the dynamics of vehicles in emergency situations on curves were analyzed. A biaxial four-wheel vehicle was simplified to a single model. Considering the braking process, dynamics, force distribution, and stability, a stopping sight distance of the curve braking calculation model was built. Then a driver-vehicle-road simulation platform was built using multibody dynamic software. The vehicle test of brake-in-turn was realized in this platform. The comparison of experimental and calculated values verified the reliability of the computational model. Eventually, the experimental values and calculated values were compared with the stopping sight distance recommended by the Highway Route Design Specification (JTGD20-2006); the current specification of stopping sight distance does not apply to cornering brake sight distance requirements. In this paper, the general values and limits of the curve stopping sight distance are presented.

1. Introduction

The sight distance is an important index in ensuring road safety and one of the compulsory indexes of road engineering construction standards. While overtaking on horizontal and vertical curves, short sight distance is a major reason for traffic accidents [1]. There are four types of sight distances: stopping sight distance, passing sight distance, give-way sight distance, and overtaking sight distance. Currently, the criterion of sight distance is quite different around the world [2, 3]. The national rules for various types of sight distance are clearly defined; however, stopping sight distance recommended by the Highway Route Design Specification (JTG D20-2006) and Guidelines for Safety Audit of Highway (JTG/T B05-2004) is quite different [4]. In addition, most researchers are focused on the study of automatic calculation of sight distance and three-dimensional analysis of sight distance [5–10], while less are involved in the accuracy and rationality of the sight distance of the model itself. Yuan et al. [11] inferred straight-line braking distance based on kinematics. Compared with straight-line braking, cornering brake had longer braking distance and poorer stability and thus drivers were more prone to making mistakes, which resulted in drivers losing control over their vehicles [12]. However, there has been no research on stopping sight distance in horizontal curves. In response to these issues, this study first analyzed the drivers' braking process and then inferred cornering braking distance based on kinematics and applied the ADAMS software to simulate cornering brake. Finally, it presents the minimum value of the curve stopping sight distance.

Previous study on the sight distance is mainly through the following three methods: mathematical model calculation, experimental data analysis, and simulation test. The mathematical model calculation is a traditional way; Peng Yuhua obtained the linear sight distance equations based on the expressions of calculating the coordinate and direction angle of the random position on the road alignment [13]. Liao et al. investigated a method of using highway 3D dynamic sight distance to represent the available sight distance, which considered the influencing factors of combination of horizontal and vertical alignment, the driver's dynamic visual field, and the illumination angle of the vehicle head lamps. And

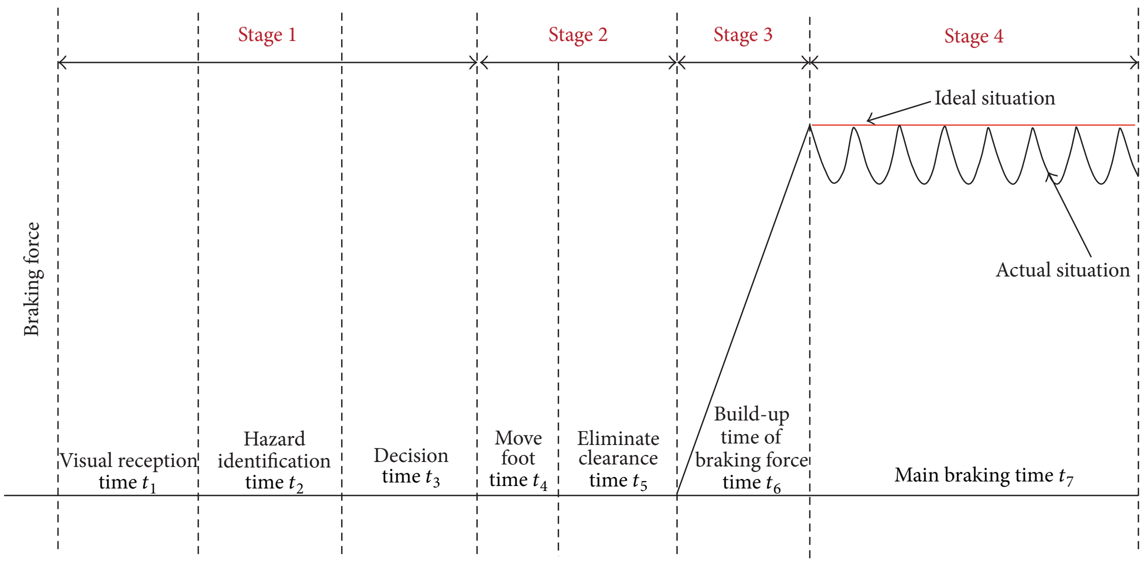

FIGURE 1: Braking process analysis.

the method was verified by a real case study [14]. The above study mainly calculated the sight distance from the aspect of the road alignment, but the kinematic characteristics of the vehicle itself were not fully taken into account.

Compared to experimental test, simulation test has the advantage of low cost and short period, whose validity is verified by numerous previous researches. Delaigue and Eskandarian through the use of MATLAB and SIMULINK established the brake model, which is able to simulate straight-line braking events under various vehicle, driver, and environment conditions and predict various conditions' braking distance. The comparisons of stopping distances between model and experiment show the validation of the simulations [15]. Pang focused on the sufficient sight distance at unsignalized intersection and the effect of sight distance on drivers' behaviors. With the use of driving simulation system, drivers' performance with different conditions can be simulated to analyze drivers' sight distance demand [16]. Previous study did not study the stopping distance on the braking-in-turn. Thus this thesis uses ADAMS software to simulate cornering brake and obtain the stopping sight distance on the curve.

2. Braking Process Analysis

When a vehicle brakes urgently, the process of the driver's operation can be divided into four stages. The entire process is shown in Figure 1.

Stage 1 is the brake reaction time. It is made up of the time taken to realize and identify hazard and the time spent to decide to brake. It can be expressed as

$$t_r = t_1 + t_2 + t_3. \quad (1)$$

Stage 2 is the braking harmony time, which includes the time to move the foot from the accelerator pedal to the brake pedal and the time consumed to eliminate the clearance of the brake pedal:

$$t_a = t_4 + t_5. \quad (2)$$

Stage 3 is the build-up time of the braking force from the emergence of the brake force to braking force up to the maximum value. It can be expressed as

$$t_s = t_6. \quad (3)$$

Stage 4 is the main braking time; that is,

$$t_l = t_7. \quad (4)$$

The braking force is assumed to be a constant value by the calculation model provided by the Highway Route Design Specification (JTG D20-2006) and the study model used by related scholars [11, 17], but in fact if the maximum braking intensity has remained constant, it will cause the wheels to lock and skid, as well as causing side impacts and other dangerous states [19]. As shown in stage 4 of Figure 1, the braking force was corrected to a certain extent according to the safe driving behavior of a proficient driver and to widely used ABS control technology in modern cars.

3. Cornering Brake Dynamics Analysis

For a biaxial four-wheel vehicle, if the variation of the wheel loads of two wheels on the same axle is ignored, the two wheels on the respective axle can be substituted by a wheel, which simplifies the vehicle as a single model shown in Figure 2. The center of the mass of the vehicle is M whose speed is $V_M = v$ along the tangential direction of the lane curve and on a straight line with tangential acceleration of $\dot{v}$. Centripetal acceleration (V^2/R) of M points to the center of curvature. Road curve radius is R. The angle β between

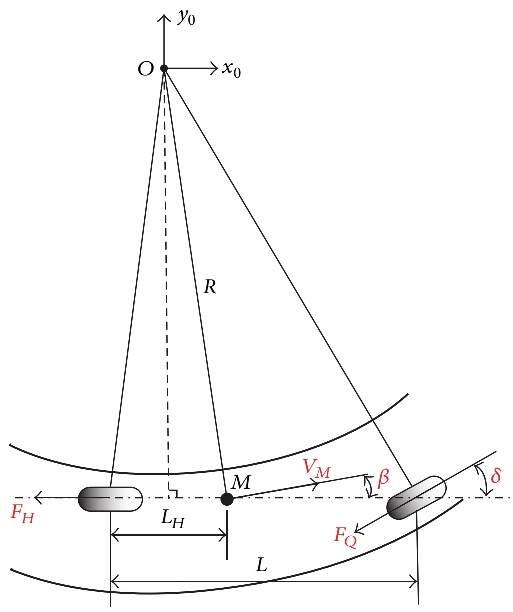

FIGURE 2: Force analysis of the single vehicle model and its dynamic parameters.

V_M and the longitudinal axis of the vehicle is called the side-slip angle. The vehicle was placed in a fixed X-Y coordinate system; δ is the front wheel steering angle. The braking force of the front wheels of the vehicle given by the brake is F_Q, while for the rear wheels, it is F_H. Wheelbase of the vehicle is L and the distance between the centroid of the vehicle and rear wheels is L_H.

It is assumed that the turning radius of the vehicle is constant, which is equal to the circular curve radius. Therefore, in the tangential direction of the running speed, the following is obtained:

$$F_H \cos\beta + F_Q \cos(\delta - \beta) = Ma, \tag{5}$$

where the braking deceleration of the vehicle is a and δ is the front wheel input angle equal to $\delta_0 + k_1(V^2/R)$. The side-slip angle is β which can be expressed as $\beta_0 - k_2(V^2/R)$. The initial steering angle of the vehicle entering the circle curve (Ackerman angle) is δ_0 which is equal to L/R and β_0 is initial side-slip angle, defined as L_H/R. Both k_1 and k_2 are determined by the stiffness of the front and rear tires and the wheelbase.

In addition, under the conditions of the ideal distribution of braking force, each of the relative deceleration values are given by the following relation:

$$\mu_Q = \mu_H. \tag{6}$$

The ideal braking force can be expanded as follows:

$$\begin{aligned}\frac{F_Q}{F_H} &= \frac{F_{fQ}}{F_{fH}} = \frac{\mu_Q F_{NQ}}{\mu_H F_{NH}} = \frac{F_{NQ}}{F_{NH}} = \frac{G(L - L_H)/L}{GL_H/L} \\ &= \frac{L_H}{L - L_H}.\end{aligned} \tag{7}$$

Therefore, the braking force of the front wheels can be computed by

$$F_Q = \frac{L_H}{L} F_Z. \tag{8}$$

The braking force of the rear wheel is

$$F_H = \frac{L - L_H}{L} F_Z, \tag{9}$$

where F_{NQ} is the longitudinal force of front wheel, F_{NH} is longitudinal force of the rear wheel, and F_Z is the braking force of the vehicle.

4. Braking Distance Analysis Based on Kinematics

According to the analysis in Figure 1, the braking distance consists of three parts: (1) The distance that the vehicle has covered within $t_r + t_a$ at the speed of initial velocity V. It can be calculated by

$$s_1 = v_0 (t_r + t_a). \tag{10}$$

(2) The distance covered within the build-up time of the braking force. Assuming that the braking force increases linearly, the following is obtained:

$$\begin{aligned}s_2 &= \int_0^s ds = \int_0^{t_s} v\,dt = \int_0^{t_s} \left(v_0 - \frac{a_{\max}}{2t_s} t^2\right) dt \\ &= v_0 t_s - \frac{1}{6} a_{\max} t_s^2.\end{aligned} \tag{11}$$

After an increase in the braking force, the velocity is calculated as

$$v_1 = v_0 - \int_0^{t_s} \frac{a_{\max}}{t_s} t\,dt = v_0 - \frac{a_{\max} t_s}{2}. \tag{12}$$

(3) The distance covered within the main braking time. According to (5), (8), and (9), the braking deceleration of the vehicle is

$$a = \frac{[(L - L_H)\cos\beta + L_H \cos(\delta - \beta)] F_Z}{ML}. \tag{13}$$

Based on ABS braking force control theory, the variation of the braking force is obtained and can be approximated by a sine function:

$$F_Z = F_{\mathrm{ZMAX}} - F_A |\sin \omega t|, \tag{14}$$

where F_{ZMAX} is the maximum of the braking force, F_A is the amplitude of the braking force, and ω is the rate of the change of the braking force ($\omega = 2\pi/T$, where T is the cycle of the braking force).

According to (13) and (14), the braking deceleration of the vehicle is expressed in another form:

$$\begin{aligned}a &= \frac{[(L - L_H)\cos\beta + L_H \cos(\delta - \beta)](F_{\mathrm{ZMAX}} - F_A |\sin \omega t|)}{ML} \\ &= K(a_{\max} - A|\sin \omega t|),\end{aligned} \tag{15}$$

Table 1: Car structure parameters.

Weight (kg)	Wheelbase (m)	Distance between CG and back axle (m)	Cornering stiffness (N/rad)		Braking torque (N∗m)	
			Front wheel	Rear wheel	Front wheel	Rear wheel
1437	2.56	1.33	800	800	1000	1700

where $K = ((L - L_H)\cos\beta + L_H\cos(\delta - \beta))/L$ is the structural parameter of the vehicle, $A = F_A/M$ is the dynamic parameter of the vehicle, $a_{\max}$ is the maximum deceleration of the vehicle.

The vehicle speed at any time can be calculated by

$$\int_{v_1}^{v} dv = \int_0^{t_l} a\,dt. \tag{16}$$

Therefore,

$$v = v_1 - \int_0^{t_l} a\,dt. \tag{17}$$

For a speed of $v = 0$, the braking time is given by the following relation:

$$t_l = \frac{v_1}{Ka_{\max} - A/\sqrt{2}}. \tag{18}$$

Based on (17) and (18), the distance during braking can be found:

$$\begin{aligned} s_3 &= \int_0^s ds = \int_0^{t_l} v\,dt = \int_0^{t_l}\left(v_1 - \int_0^t a\,dt\right)dt \\ &= \frac{v_1^2}{2\left(Ka_{\max} - A/\sqrt{2}\right)}. \end{aligned} \tag{19}$$

(4) The total braking distance. According to (10), (11), and (19), it is found that

$$\begin{aligned} s &= s_1 + s_2 + s_3 \\ &= v_0\left(t_r + t_a + t_s\right) - \frac{1}{6}a_{\max}t_s^2 + \frac{v_1^2}{2\left(Ka_{\max} - A/\sqrt{2}\right)}. \end{aligned} \tag{20}$$

As shown in the literature [3, 11], the build-up time of the braking force is short; hence, the speed of the vehicle during this process is almost constant ($v_1 \approx v_0$); therefore,

$$\begin{aligned} s &= s_1 + s_2 + s_3 \\ &= v_0\left(t_r + t_a + t_s\right) - \frac{1}{6}a_{\max}t_s^2 + \frac{v_0^2}{2\left(Ka_{\max} - A/\sqrt{2}\right)}. \end{aligned} \tag{21}$$

The stopping sight distance calculation model shows that the stopping sight distance of the cornering brake is not only related to the braking deceleration of the vehicle, the friction coefficient of the road, and the driver's reaction time but also correlated with the circular curve parameters and the structure of the vehicle. The model indicates that the driver-vehicle-road system has an impact on the stopping sight distance.

5. Cornering Brake Simulation Analysis Based on Multibody Dynamics

5.1. Construction of Simulation System. A virtual simulation analysis can be performed using the multibody dynamics simulation software ADAMS [20]. The core of the simulation system includes vehicle model, road model, driver model, tire model, and the simulation settings. In this study, the 97-degree-of-freedom general car model was used. This feature comes with the ADAMS/car software and its parameters are shown in Table 1. The driver-vehicle-road simulation system introduces an open-loop control method for driving and builds a slippery circular curve road model which meets the Highway Route Design Specification (JTG D20-2006) [17] requirements. The super elevation rate of the circular curve is 8% and the Fiala tire model [20] is selected, conforming to the highway cornering brake simulation requirements.

5.2. Simulation Setting. A simulation analysis was carried out for cornering brake, one of the most dangerous common situations in daily driving. In this test simulation, the driver drives the vehicle from a straight-line approach road (100 m) into the test line and then the vehicle accelerates until it achieves lateral acceleration. Once the vehicle reaches the designed lateral acceleration, the drive maintains the speed and turns radius to reach a steady-state value after a period of time. Then, the drive adjusts the steering value, maintains the original turning radius (circular curve radius of road), and brakes (brake for the BF), so that the vehicle achieves a targeted deceleration a. Within the set duration, the deceleration remains unchanged until the speed reduces to 2.5 m/s or less. After the simulation, the braking distance of the vehicle under different circular curves is measured. The car-road simulation model is shown in Figures 3 and 4.

5.3. Parameter Setting. The experimental results in the literature [21] show that the braking deceleration should not exceed 3 m/s^2 in nonemergency braking situations and the maximum deceleration on wet surfaces should not exceed 2 m/s^2. Therefore, in this study, values of $a_1 = 2$ m/s^2 and $a_2 = 3$ m/s^2 were selected. The maximum braking time, as an initial value, was calculated by the chosen braking force. The experimental trigger condition was set based on different circular curve radii and the speed of vehicle (V^2/R).

In the validation experiment, where the curve radius affects the braking distance, vehicle and other road parameters were kept constant on curve radii of 300 m, 400 m, 500 m, and 600 m and at the speed of 80 km/h and a deceleration of 3 m/s^2.

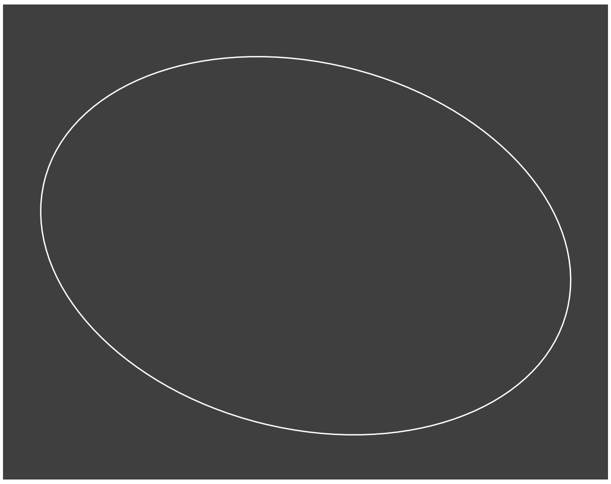

Figure 3: Curve.

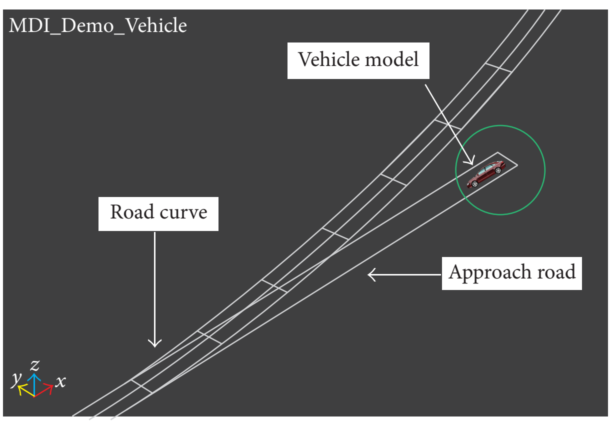

Figure 4: Driver-vehicle-road simulation system.

5.4. Simulation Results and Analysis. Figure 5 shows the same vehicle trajectory on four different curve radii at the same initial velocity and deceleration. Based on the simulation analysis, the relationship between the radius and the curve stopping sight distance is shown in Figure 6.

The vehicle cornering brake simulation under different braking decelerations and different circular curve parameters is completed. The result for the braking trajectory of vehicle is shown in Figures 7 and 8. The curve of stopping sight distance can be obtained by measuring the length of the braking trajectory of the vehicle combined with the driver's recognition reaction and the distance of the vehicle running between braking harmony time and build-up time of braking force (shown in Table 2).

Comparing the results from Figures 7 and 8, conclusions can be obtained as follows. When the $2\,m/s^2$ braking deceleration is applied, the vehicle can be stopped relatively stable. When the applied braking deceleration is $3\,m/s^2$, because at this time the tire/road interface maximum coefficient of adhesion is close to the maximum coefficient friction of the road, at a speed of 102 km/h the vehicle slides off the road; at 85 km/h and 68 km/h though the vehicle does not exhibit

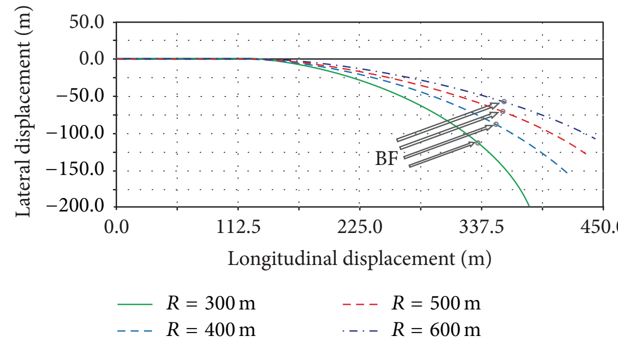

Figure 5: Braking trajectory of the vehicle in different radius curves.

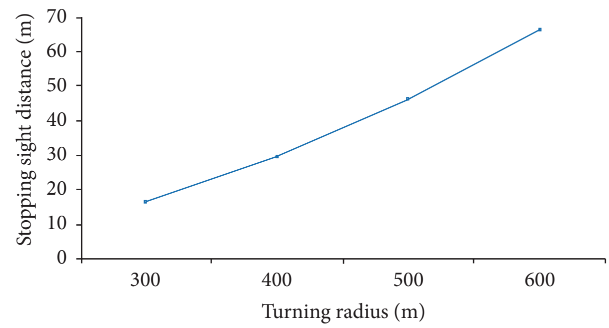

Figure 6: Relationship between curve radius and curve stopping sight distance.

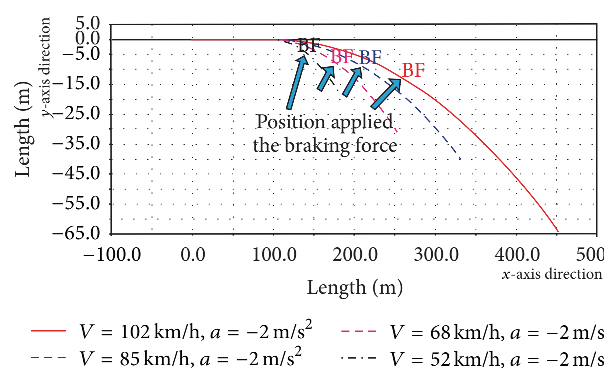

Figure 7: Vehicle trajectory with a braking deceleration of $2\,m/s^2$.

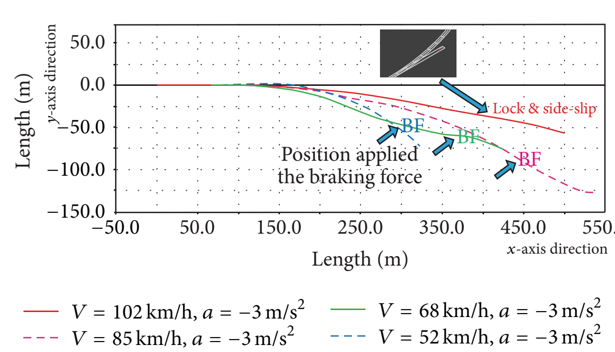

Figure 8: Vehicle trajectory with a braking deceleration of $3\,m/s^2$.

Table 2: Comparison of various stopping sight distances.

Design/running velocity (km/h)	Different circular curve parameters [17]		Specification values [13] (m)	Literature values [11] (m)	Equation (21) values (m)	Running distance within $t_r + t_a + t_s$ (m)	Experimental values (m)		Experimental final values (m)	
	R	μ					a_1	a_2	a_1	a_2
120/102	1000	0.29	210	191.72	228.1	76.4	203.1	Rollover	279.5	Rollover
100/85	700	0.30	160	143.37	169.1	63.7	142.3	101.2	206.0	166.9
80/68	400	0.31	110	101.58	118.4	51.0	91.8	65.3	142.8	118.3
60/52	200	0.33	75	72.09	78.5	39.1	58.2	43.4	97.3	84.5

Note: μ is the friction coefficient of the wet road; Specification values and literature values are obtained by straight-line brake stopping sight distance; $t_r + t_a + t_s = 2.7$ s (according to provisions of Technical Standard of Highway Engineering [18], the value of braking reaction time is 2.5 s; according to Yuan et al. [11] research, the build-up time of the braking force is 0.2 s); $a = 3\,\text{m/s}^2$ in (21); the final experimental values are obtained from experimental values plus the running distance within $t_r + t_a + t_s$.

Table 3: Curve stopping sight distance.

Design velocity (km/h)	120	100	80	60
Limits of the curve stopping sight distance (m)	230	170	120	85
The general stopping sight distance (m)	280	205	145	100

Note: the lager value of final experimental value for (21) and $a = 3\,\mathrm{m/s^2}$ is rounded to get the limits of the curve stopping sight distance. The general stopping sight distance is obtained by rounding final experimental value for $a = 2\,\mathrm{m/s^2}$.

lateral instability and it is in an unstable state. Thus, we should not use the maximum coefficient friction of the road to calculate the stopping sight distance.

A comparison of the values of the four stopping sight distances shows that the current specification for stopping sight distance does not apply to the curve stopping sight distance requirements. In fact, the vehicle needs longer curve stopping sight distance and even a longer stopping sight distance is needed to meet the requirements of cornering braking stability. The comparison of simulation experiment values and model values shows that the derived model values and experimental values are basically similar, which verifies the applicability and reliability of the calculation model. Therefore, it can be used as a calculation model of the curve stopping sight distance.

Comprehensive analysis of four kinds of stopping sight distances gives the minimum limits of the curve stopping sight distance. The general stopping sight distance meets comfort and stability of braking-in-turn (Table 3).

6. Conclusion

Current studies of stopping sight distance braking model only consider the straight-line braking problems and do not study the vehicle stopping sight distance for cornering brake, which is a dangerous situation. In addition, current studies rarely consider the effect of the structure of the vehicle, road alignment parameters, and stopping sight distance. This paper overcomes the shortcomings of above research, and a stopping sight distance calculation model for cornering brake is deduced considering vehicle dynamics. A simulation experiment using ADAMS software is carried out, verifying the reliability of the model. Finally, the paper provides the minimum limits of the curve stopping sight distance and the general stopping sight distance met comfort and stability of car braking-in-turn, which provides reference for road design research officers. It takes further studies on large heavy vehicles with higher requirements for sight distance.

Competing Interests

The authors declare that they have no competing interests.

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References

[1] Y.-L. Pei, *Road Traffic Accident Causes Analysis and Countermeasures Research*, School of Transportation, Southeast University, Nanjing, China, 2002.

[2] I. Taignidis and G. Kanellaidis, "Required stopping sight distance on crest vertical curves," *Journal of Transportation Engineering*, vol. 127, no. 4, pp. 275–282, 2001.

[3] Y. Hassan and S. M. Easa, "Modeling of required preview sight distance," *Journal of Transportation Engineering*, vol. 126, no. 1, pp. 13–20, 2000.

[4] Y.-P. Wang, S.-L. Zhao, and L. Zhou, "Highway stopping sight distance study," *Transportation Standardization*, vol. 228, pp. 131–137, 2010.

[5] G. Nehate and M. Rys, "3D calculation of stopping-sight distance from GPS data," *Journal of Transportation Engineering*, vol. 132, no. 9, pp. 691–698, 2006.

[6] M. Z. A. Ali, S. M. Easa, and M. Hamed, "Stop-controlled intersection sight distance: minor road on tangent of horizontal curve," *Journal of Transportation Engineering*, vol. 135, no. 9, pp. 650–657, 2009.

[7] S. R. Davoodi, H. Hamid, M. Pazhouhanfar, and J. W. Muttart, "Motorcyclist perception response time in stopping sight distance situations," *Safety Science*, vol. 50, no. 3, pp. 371–377, 2012.

[8] P. Zhang, "Overview of three-dimensional (3D) analysis of sight distance," *Highway and Transportation Research (Application Technology)*, no. 6, pp. 202–204, 2012.

[9] Z. Wang, J.-B. Liu, and T.-F. Guo, "Calculation method and detection technology of highway space sight distance," *Journal of Chang'an University (Natural Science Edition)*, no. 6, pp. 44–47, 2007.

[10] X.-Y. Liu, M. Zhou, and T.-F. Guo, "Analysis and verification of highway sight distance," *Journal of Highway China*, vol. 23, supplement 2, pp. 36–41, 2012.

[11] H. Yuan, G.-F. Shi, X.-M. Huang, and J.-C. Cheng, "Stopping sight distance brake model," *Journal of Southeast University (Natural Science Edition)*, vol. 39, no. 4, pp. 859–862, 2009.

[12] Z.-M. Xu, Z.-C. Su, Z.-F. Zhang, and F. Yu, "Research on the driver model of horizontal trajectory control of vehicle turning brake," *Highway Transportation Science and Technology*, no. 8, pp. 146–150, 2008.

[13] Y.-H. Peng, S.-W. Yang, and F.-R. Shi, "New method for calculating net-transverse distance," *Journal of Chang'an University (Natural Science Edition)*, vol. 23, no. 6, pp. 33–35, 2003.

[14] J.-H. Liao, C.-F. Shao, H.-B. Wu, Y.-X. Sun, and S.-L. Wang, "Calculation and assessment technique of highway 3D dynamic sight distance," *Journal of Jilin University (Engineering and Technology Edition)*, vol. 43, no. 3, pp. 640–645, 2013.

[15] P. Delaigue and A. Eskandarian, "A comprehensive vehicle braking model for predictions of stopping distances," *Proceedings of the Institution of Mechanical Engineers, Part D*, vol. 218, no. 12, pp. 1409–1417, 2004.

[16] H.-T. Pang, *Safety Sight Distance at Unsignalized Intersection Research Based on Driving Simulation Experiments*, Beijing Jiaotong University, Beijing, China, 2013.

[17] Ministry of Transport of the People's Republic of China, *JTGD20-2006 the Highway Route Design Specification*, People's Communications Press, Beijing, China, 2006.

[18] Ministry of Transport of the People's Republic of China, "Technical standard of highway engineering," Tech. Rep. JTGB01-2003, People's Communications Press, Beijing, China, 2003.

[19] J. Li, F. Yu, J.-W. Zhang, and J.-Z. Feng, "Simulation of vehicle steering anti-lock braking system," *Journal of System Simulation*, vol. 11, no. 6, pp. 789–793, 2001.

[20] L.-P. Chen, Y.-Q. Zhang, W.-Q. Ren, and G. Qin, *Mechanical System Dynamics Analysis Adams Application Tutorial*, Tsinghua University Press, Beijing, China, 2005.

[21] G.-J. Shen, Z.-Q. Liu, and L.-J. Meng, "Analysis of the longitudinal dynamics test on No. T41/42 train from West Beijing Station to Xi'an Station," *Rolling Stock*, vol. 40, no. 11, pp. 8–9, 2000.