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REVISION OF CALCULATION OF STOPPING SIGHT DISTANCE

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Abstract. Stopping Sight Distance (SSD) is a critical parameter for roadway geometric design and safety evaluation. It experienced several revisions in AASHTO Green Books (A Policy on Geometric Design of Highways and Streets) since 1940. This paper firstly lists the revision history of SSD model in the last 70 years in the USA as example, and then points out that the more critical conditions for vehicles driving at curves with superelevation should be used for SSD calculation. Based on that, this paper conducts a revised SSD calculation model which is universal and more reasonable for SSD calculation. Finally, a case study was completed to show the difference between the existing and the revised calculations of SSD. The revised SSD model suggested basically increasing longer SSDs as speed varies from 30 km/h to 110 km/h, and a little decline at speed 120 km/h.

Keywords: stopping sight distance (SSD), roadway geometric design, curve, highway alignment, driving speed, highway safety.

1. Introduction

Sight distance is a primary element in roadway geometric design. From a geometric design standpoint, the min sight distance available on a roadway should be long enough to allow a vehicle traveling at or around the design speed to stop before reaching a stationary object in its path. As a control index, the Stopping Sight Distance (SSD) is relatively important among various sight distances. The sight distances such as decesion sight distance and passing sight distance are all calculated based on SSD. To simplify the relations of SSD with vehicle and roadway, this paper takes traditional vehicle dynamics and roadway geometry as consideration for SSD calculation, although some researches verified that the real on-site SSDs are also affected by some factors such as the Anti-lock braking system (ABS) and the roughness of roadway surface, etc. (Bogdevičius, Vladimirov 2006; Durth, Bernhard 2000; Greibe 2008; Mavromatis et al. 2005).

The current procedures for determining SSD are intended to allow a normally alert passenger-car driver, traveling at or around the design speed on wet pavement, to react and bring the vehicle to a stop before striking a stationary object in its path. The basic calculation model for this situation was formalized by American Association of State Highway Officials (AASHO) in 1940. Although the calculation model has remained unchanged, adjustments in calculation model parameters have been made in several AASHO and American Association of State Highways and Transportation Officials (AASHTO) publications over the past few decades. Table 1 below is a summary of these changes since 1940.

The significant change in determining the SSD requirement is the use of a comfortable deceleration rate rather than a friction factor at A Policy on Geometric Design of Highways and Streets (2001) based on the findings and recommendations reported in the NCHRP Report 400 Determination of Stopping Sight Distances (Fambro et al. 1997; Prosser 2005). The authors also made similar research work (Yuan et al. 2009) although the current SSD calculation in almost all the other countries of the world including China's Design Specification for Highway Alignment (JTG D20-2006) is still based on friction factor. However, different opinions exist concerning the appropriateness of the calculation model and the values of parameters used to determine the min required SSD (Hall, Turner 1988; Olson et al. 1984). This paper analyzes and revises the existing SSD calculation model which is based on driving at straight section, not considering the influence of curve and cross slope variation such as superelevation. Therefore, through refining the physical calculation model with consideration of the influence of driving at curve section, a more reasonable formula of SSD calculation is presented.

2. The existing SSD calculation model and formulas

One of the most important requirements in highway design is to provide adequate SSD at every place along the roadway. It is calculated using basic principles of physics and relationships among the various design parameters. As all known, SSD is the sum of two components, brake reaction distance S_1 (distance traveled from the instant of object detection to the instant the brake is applied) and braking distance S_2 (distance traveled from the instant the brake is applied to when the vehicle is decelerated to a stop).

Perception-reaction time for SSD is defined as the interval of time between the instant that the driver recognizes the existence of an object or hazard on roadway ahead and the instant that the driver actually applies the brakes or makes an evasive maneuver. This interval includes the time required to make the decision that a stop or path correction is necessary. So the reaction distance can be expressed by the Eq (1):

$$S_1 = \frac{Vt}{3.6},\tag{1}$$

where V – vehicle speed, km/h; t – perception-reaction time. For approx 90% of drivers in the various studies mentioned, a reaction time of 2.5 s was found to be adequate (Fambro *et al.* 1997; Johansson, Rumar 1971; Normann 1953; Shi *et al.* 2010), although some research works based on field measurement suggested that a 2.0 s is enough (Durth, Bernhard 2000; Mavromatis *et al.* 2005). The approx brake distance of a vehicle on a level terrain roadway may be determined by the Eq (2):

$$S_2 = \frac{V^2}{25.92a},$$
 (2)

where V – vehicle speed, km/h; a – driver deceleration, m/s².

The existing formula adopts a physics calculation model in which vehicles travel at a straight roadway section. Thus, under this condition for level terrain, only the friction between tires and roadway contributes to a stop (Fig. 1).



Fig. 1. Traveling at level terrain and straight roadway section

Table 1. Changes in the 6 parameters used for SSD calculation

Reference (year, title)	Speed of calculation	Perception- reaction time, s	Design pavement/stop	Friction factors or deceleration rate	Eye height, m	Object height, m
1940, A Policy on Sight Distance for Highways	Design speed	3.0 at 50.7 km/h or 2.0 at 118.3 km/h	Dry/Locked- wheel	Ranges from 0.50 at 50.7 km/h to 0.40 at 118.3 km/h	1.37	0.10
1954, A Policy on Geometric Design of Rural Highways	85–95% of design speed	2.5	Wet/Locked- wheel	Ranges from 0.36 at 50.7 km/h to 0.29 at 118.3 km/h	1.37	0.10
1965, A Policy on Geometric Design of Rural Highways	80–93% of design speed	2.5	Wet/Locked- wheel	Ranges from 0.36 at 50.7 km/h to 0.27 at 118.3 km/h	1.14	0.15
1971, A Policy on Geometric Design of Highways and Streets	Min. – 80 to 93% of design speed Des. – design speed	2.5	Wet/Locked- wheel	Ranges from 0.35 at 50.7 km/h to 0.27 at 118.3 km/h	1.14	0.15
1984 and 1990, A Policy on Geometric Design of Highways and Streets	Min. – 80 to 93 % of design speed Des. – design speed	2.5	Wet/Locked- wheel	Slightly higher at higher speeds than 1970 values	1.07	0.15
1994, A Policy on Geometric Design of Highways and Streets	Min. – 82 to 100 % of design speed Des. – design speed	2.5	Wet/Locked- wheel	Ranges from 0.40 at 30 km/h to 0.28 at 120 km/h	1.07	0.15
2001 and 2004, Policy on Geometric Design of Highways and Streets	Design speed	2.5	Wet/Locked- wheel	Deceleration rate 3.4 m/s ²	1.07	0.6

Note: Min - minimum speed; Des - disarable speed.

Friction between tires and roadway can be expressed by the Eq (3):

1

$$F = Gf = ma, \tag{3}$$

(4)

where F – friction between tires and roadway, N; G –vehicle weight, N; f – coefficient of friction between tires and roadway; m – vehicle mass, kg; a – driver deceleration, m/s². Then

$$a = gf$$
,

where g – acceleration of gravity, m/s².

Thus the existing Eqs for SSD calculation are:

$$S_2 = \frac{V^2}{25.92gf} \approx \frac{V^2}{254f},$$
 (5)

$$S = S_1 + S_2 = \frac{Vt}{3.6} + \frac{V^2}{254f}.$$
 (6)

For driving at straight longitudinal slope sections, the Eq has a little change as shown at Eq (7).

$$S = \frac{Vt}{3.6} + \frac{V^2}{254(f \pm i)},\tag{7}$$

where i – grade: + for upgrade, – for down grade, %.

Some countries like Austria, Germany and Greece use a slightly different SSD model, which incorporates the effect of a speed-dependent longitudinal friction factor and the aerodynamic drag force on the decelerating vehicles, as shown in Eq (8) (Harwood *et al.* 1995).

$$S = \frac{Vt}{3.6} + \frac{1}{127} \int_{V}^{0} \frac{V}{f_T(V) + i + \frac{F_L}{mg}},$$
(8)

where $f_T(V)$ – speed dependent longitudinal friction factor; F_I – aerodynamic drag force, N.

3. Revision of SSD calculation model and formulas

The existing SSD calculation model is simple as it only considers the situation of driving at straight section, ignoring the situation of driving at curve section, the likely accidentprone area. Therefore, there appeared documents revising the SSD application in practice. Among these documents, 3D-alignment SSD analysis, field measurement based parameters revision for perception-reaction time; deceleration rate and coefficient of friction, as well as reliability-based SSD calculation are most common (Arndt *et al.* 2010; Easa 2009; Greibe 2008; Nehate, Rys 2006; Sarhan, Hassan 2009). However, these revisions did not pay attention to the SSD model itself, still taking driving at straight section as default.

Obviously, driving at curve section with superelevation is less safe and faces more safety concern caused by sight distance especially at with small horizontal radii (Dissceti 2010). Therefore, driving at curve section should be used for SSD calculation model.

As shown in Figs 2, 3, when vehicle is traveling at curve, the physical calculation model of braking in limit state of slip can be defined.



Fig. 2. Traveling at curve with superelevation section



Fig. 3. Traveling at curve section, where above: a_0 – acceleration centripetal, m/s²; a – driver deceleration, m/s²; e – superelevation rate; R – horizontal radius, m

Compared with Figs 1, 2 in critical condition of slip, that differs from what takes place on straight and level sections (note: the direction of friction is reverse to that of vehicle slip).

$$G\sin\alpha + F\cos\beta = ma\cos\alpha,\tag{9}$$

$$F\sin\beta = ma,$$
 (10)

 $\cos \alpha = 1$, $\sin \alpha \approx \tan \alpha = e$ has been assumed for α is generally tiny. Substituting for $F = Nf = G \cos \alpha f$ and

$$a_0 = \frac{\left(\frac{V}{3.6}\right)^2}{R} \text{ in Eqs (9) and (10), then}$$
$$gi + gf \cos\beta = \frac{\left(\frac{V}{3.6}\right)^2}{R}, \tag{11}$$

$$gf\sin\beta = a. \tag{12}$$

Now Eq (11) can be written as:

$$\cos\beta = \frac{\left(\frac{V}{3.6}\right)^2}{\frac{R}{gf}} - ge,$$
 (13)

then

$$\sin\beta = \sqrt{1 - \frac{\left(\frac{\left(\frac{V}{3.6}\right)^2}{R} - ge\right)^2}{g^2 f^2}}.$$
 (14)

Substituting for sin β from Eq (14) in Eq (12), then

$$a = \sqrt{g^2 f^2 - \left(\frac{\left(\frac{V}{3.6}\right)^2}{R} - ge\right)^2}.$$
 (15)

Compared Eq (15) with Eq (4), it is found when vehicles move on curve sections, largest deceleration of vehicle is less than that on level sections. It is also affected by vehicle speed *V*, curve radius *R* and superelevation rate *e*. Moreover, if $R = +\infty$ and e = 0 (level terrain condition), Eq (15) will be same as Eq (4). So Eq (15) is applicable to much more cases than Eq (4) which is a special case of Eq (15).

Substituting for a from Eq (15) in Eq (2), then

$$S_{2} = \frac{V^{2}}{25.92} \left[g^{2} f^{2} - \left(\frac{\left(\frac{V}{3.6} \right)^{2}}{R} - ge \right)^{2} \right]^{2}$$
(16)

So, the braking distance gap Δ_{S_2} by two models is

$$\Delta_{S_2} = \frac{V^2}{25.92} \left[g^2 f^2 - \left(\frac{\left(\frac{V}{3.6} \right)^2}{R} - ge \right)^2 - \frac{V^2}{254f} \right].$$
(17)

4. Case study

Based on Eq (17) Table 2 gives the revised braking distances at 5 max superelevation rates corresponding the min horizontal radii for design speeds ranging from min speed 30 km/h to max speed 120 km/h in comparison with those calculated using the 1994 Green Book (metric).

Table 2. Distance gap between the existing braking distance and the revised value

Speed, km/h	е	R, m	Braking distance, m	Revised value, m	Distance gap, m
30	0.04	35		9.69	0.89
	0.06	30		9.87	1.07
	0.08	30	8.8	9.62	0.82
	0.10	25		9.97	1.17
	0.12	25		9.70	0.90
	0.04	60		18.53	1.93
	0.06	55		18.51	1.91
40	0.08	50	16.6	18.59	1.99
	0.10	45		18.82	2.22
	0.12	45		18.27	1.67
	0.04	100		31.45	3.35
50	0.06	90		31.56	3.46
	0.08	80	28.1	31.94	3.84
	0.10	75		31.75	3.65
	0.12	70		31.68	3.58
	0.04	150		48.13	5.23
	0.06	135		48.21	5.31
60	0.08	125	42.9	47.95	5.05
	0.10	115		47.92	5.02
	0.12	105		48.21	5.31
70	0.04	215		69.67	7.47
	0.06	195		69.47	7.27
	0.08	175	62.2	69.80	7.60
	0.10	160		69.89	7.69
	0.12	150		69.40	7.20
80	0.04	280		94.95	11.05
	0.06	250		95.26	11.36
	0.08	230	83.9	94.79	10.89
	0.10	210		94.95	11.05
	0.12	195		94.66	10.76
90	0.04	375		117.96	11.76
	0.06	335		118.02	11.82
	0.08	305	106.2	117.75	11.55
	0.10	275		118.35	12.15
	0.12	255		117.96	11.76

Continued Table 2

100	0.04	490		149.29	13.69
	0.06	435		149.37	13.77
	0.08	395	135.6	148.94	13.34
	0.10	360		148.79	13.19
	0.12	330		148.76	13.16
110	0.04	625		185.01	15.01
	0.06	560		185.04	15.04
	0.08	500	170.0	185.16	15.16
	0.10	455		184.81	14.81
	0.12	415		184.87	14.87
120	0.04	870		213.90	11.60
	0.06	755		213.86	11.56
	0.08	665	202.3	213.94	11.64
	0.10	595		213.96	11.66
	0.12	540		213.80	11.50

As shown in Figs 4 and 5, braking distance gap varies from 0.82 m to 15.16 m with the max superelevation rates and design speeds. The gap looks increasing longer SSDs with speed increases from 30 km/h to 110 km/h, except a decline at speed 120 km/h.

The braking distance gap is also illustrated graphically at Fig. 5.



Fig. 4. Comparison of the two braking distances



Fig. 5. Distance gap between the two braking distances

5. Conclusions

Based on finding out the critical condition of vehicles driving at curves, a revised SSD calculation model and formulas were presented, that are universal and cover the existing SSD model and formulas where $R = +\infty$ and no superelevation.

From a case study, the revised SSD calculation formula would result basically increasing longer SSDs as speed varies from 30 km/h to 110 km/h, and a little decline at speed 120 km/h. This is intuitively explained that driving at curves requires longer SSDs than those at straights.

The revised SSD calculation model should take longitudinal slope as consideration in the following research.

Field measurement experiment at the curve section with superelevation should be designed and implemented to test the validity of the revised SSD calculation model.

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