Calculating Method and Safety Evaluation of Highway 3D Available Sight Distance

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Abstract. Visual information is the basis of highway traffic safety, which is important for a driver to take right actions in driving. From the driving theory and the driver's sight characteristics, the concept of available sight distance is put forward. According to extend and apply the theory of the spatial intervisibility between two spots, the math model of calculating and analyzing the spatial available sight distance is built up, which is solved by use of parameter equations and space conversion. On the basis of this model, the safety evaluation model and the evaluation procedures are given. At last, the effectiveness of the model is tested in practical engineering applications, and it can provide the basis for highway geometric design and safety evaluation.

Introduction

Highway geometric design has usually been considered in separate two dimensional projections of horizontal and vertical alignments[1]. Such a practice was followed mainly because three-dimensional analysis of combined highway alignments was expected to be difficult. As a result, the effect of ignoring the 3D nature of the highway alignment could not be quantified.

Topographical and economical constraints usually make it impractical to ensure that any object on the pavement surface is visible to the drivers within the normal eye sight distance. For example, the driver's line of sight on horizontal curves may be blocked by lateral obstructions such as trees, buildings, and cut side slopes. On crest vertical curves, the line of sight may be obstructed by the vertical curve itself. Also, nighttime sight distance on sag vertical curves may be limited to the farthest point covered by the vehicle headlights.

Furthermore, overpasses represent sight obstructions for the traffic below. Therefore, designers have to check the available sight distance so the designed roads will provide drivers with at least the minimum sight distance required for safe and efficient operation. Although a clear correlation is lacking, current design guides emphasize the relationship between sight distance and traffic safety[2,3]. The importance of providing adequate 3D sight distance toward a safe and efficient operation of vehicles is recognized by most highway designers. At any point on a highway, the road environment should provide a sufficient sight distance that allows drivers to safely control their vehicles. In design practice, the available sight distance(ASD) is compared to the required sight distance(RSD), which depends on the driving and controlling tasks.

The main objective of this paper is to present a mathematic model for calculating 3D ASD for combined vertical and horizontal alignments. The model represents an expansion of the 2D sight distance model[4-6] so that vertical curvature is taken into account. The usefulness of the new model is illustrated by a case study for highway safety evaluation.

Practical Concept of 3D ASD

The 3D ASD refers to the furthest distance which the driver can actually see the object on the lane of most unfavorable sight, such as alignment curve, vertical curve or influenced by road facilities, plants or other obstacle, according to the height of sight point and object point under the real 3D condition of highway area. It also can be defined as the maximum visible distance without occluded objects between the sight of driver and the object on the lane, considering the influence of highway affiliated structures.

3D ASD changes every time with the influence of highway geometric size, traffic affiliated facilities along the road and road side structures. The actual design sight distance can be estimated in real time whether it is safe for driving by means of comparing the required design sight distance with the highway 3D ASD. In this way, the shortage of sight distance can be found, which is due to not only pavement and highway geometric alignment, but also highway affiliated facilities and structures.

Mathematic Model for Calculating 3D Highway Alignment

Formulation of center-line of highway alignment

The centerline equation for the highway alignment is as follows[7-9]:

$$\begin{cases} k(s) = axs + b \\ \varphi(s) = \varphi_0 + \int_0^s k(s)ds \\ x(s) = x_0 + \int_0^s \cos\varphi(s)ds \\ y(s) = y_0 + \int_0^s \sin\varphi(s)ds \end{cases} . \tag{1}$$

Where $k(s)$ is the curvature of the curve that station is s, and in the tangent $k(s)=0$, in the curve section have a constant value $k(s)=b$, each point in the spiral section have a linear variant $k(s)=axs+b$。 φ_0 is the deflection angle of the tangent and x-axis(when the positive angle is counter-clock wise), *x(s)* and *y(s)* are the vertical and horizontal coordinates of the *s* station.

The elevation of any centerline point *z(s)*can be obtained as follows:

$$z(s) = \begin{cases} z_{fi} + G_{2i} \times (s - sv_{fi}) & s \in [sv_{fi}, sv_{0(i+1)}] \\ z_{fi} + G_{2i} \times (s - sv_{fi}) - \dfrac{|G_{1i} - G_{2i}|}{2}(s - sv_{0(i+1)})^2 & s \in [sv_{0(i+1)}, sv_{f(i+1)}] \end{cases} . \tag{2}$$

Where each vertical curve is defined by its first grade G_{1i}, second grade G_{2i}, $sv_{0(i+1)}$, and sv_{fi}=respectively, stations of the start and end point of the i_{th} vertical curve, Zfi=elevation of the end point of the i_{th} vertical curve.

The normal to the alignment centerline, normal to the direction of stations increase for tangents, can be obtained as follows:

$$N_i = -R_z(\mathrm{sgn}(\Delta_i) \bullet \frac{\pi}{2}) \bullet \frac{T(s)}{\|T(s)\|} . \tag{3}$$

Where $\boldsymbol{R}_z(\cdot)$=rotation matrix. *T(s)*=vector in the direction of the tangent that at the *s* station, can be obtained as follows:

$$T(s)=\begin{pmatrix}T_x(s)\\T_y(s)\end{pmatrix}=\begin{pmatrix}x'(s)\Big/\sqrt{(x'(s))^2+(y'(s))^2}\\y'(s)\Big/\sqrt{(x'(s))^2+(y'(s))^2}\end{pmatrix}\quad. \tag{4}$$

The unit normal vector *N(s)* that is orthogonal to *T(s)* and points toward the right-hand side of the road is then given by

$$N(s)=\begin{bmatrix}0&1\\-1&0\end{bmatrix}T(s)=\begin{pmatrix}T_y(s)\\-T_x(s)\end{pmatrix}\quad. \tag{5}$$

If there is a width *w*, then a parametric representation of the center of the travel lane is given by

$$P(s)=\begin{pmatrix}x(s)\\y(s)\end{pmatrix}+w\begin{pmatrix}T_y(s)\\-T_x(s)\end{pmatrix}\quad. \tag{6}$$

Formulation of superelevation

A lateral offset is designated a positive value whenever it lies on the right side of the centerline and a negative value on the left side. The elevation $Z^n(s)$ at a point located on the *n*th parallel alignment at the approach segment of the i_{th} horizontal curve can be calculated as follows:

$$e(s)=\begin{cases}E\left\{s,e_i,\operatorname{sgn}(\varphi_i),e_c,\operatorname{sgn}(w(n)),st_{0i}^1\right\} & sr_{0i}\le s\le sr_{fi}\\ e_i\bullet\operatorname{sgn}(\varphi_i) & s\ge sr_{fi}\end{cases}\quad. \tag{7}$$

$$Z^n(s)=Z(s)+w(s,n)\frac{e(t)}{100}\quad. \tag{8}$$

Where e_i=absolute value of the horizontal curve superelevation; sr_{0i} and sr_{fi}=respectively, start and end station of the first superelevation transition segment of the i_{th} horizontal curve; and $E\{\cdot\}$ superelevation transition function. For example, a linear superelevation transition can be expressed as

$$E\{\bullet\}=\operatorname{sgn}(w(s,n)\times((s-st_{oi})\frac{e_i\operatorname{sgn}(\varphi_i)\bullet\operatorname{sgn}(w(s,n))-e_c}{st_{fi}-st_{oi}})+e_c\quad. \tag{9}$$

Where *ec*=absolute value of the crown section side slope.

Mathematic Model for Calculating 3D ASD

Principle of 3D ASD calculation

(1) This section describes a mathematic model for calculating the 3D ASD at a single point some distance $s\in$ [0, *s* max] from the beginning of the alignment. Set sight point as the P_1, the most left edge of the target stake of the road as the P_2, the most right edge of the target stake of the road as the P_3, these 3 points constitutes a "sight triangle"[10]. As shown in Fig. 1.

(2) Disperse random surface of highway models into a number of triangular surfaces. Calculate the intersection of sight triangle and surface of highway triangular surface, and project the intersectional lines, to be an actual 3D ASD.

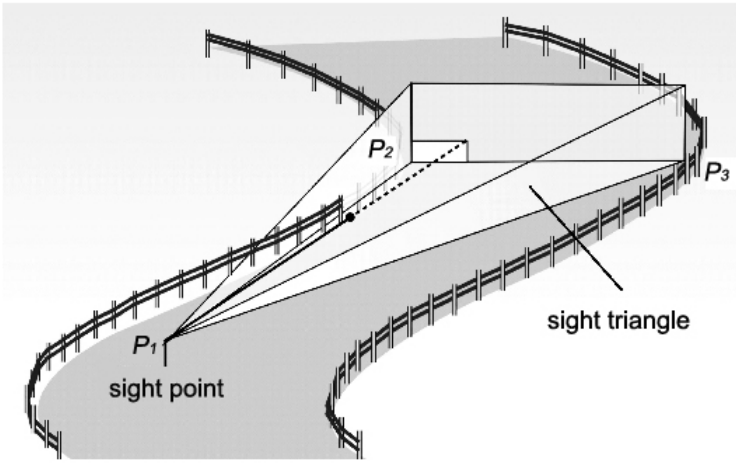

Fig. 1 Principle of 3D ASD solution

Method of 3D ASD calculation

According to the mathematic model for calculating 3D highway alignment, can calculate the three-dimensional coordinates of P_1, P_2, P_3, respectively (x_1, y_1, z_1) (x_2, y_2, z_2) (x_3, y_3, z_3).

According to P_1, P_2, P_3, can be obtained a "sight plane" as follows：

$$\begin{vmatrix} x & y & z & 1 \\ x_1 & y_1 & z_1 & 1 \\ x_2 & y_2 & z_2 & 1 \\ x_3 & y_3 & z_3 & 1 \end{vmatrix} = 0 \quad . \tag{10}$$

It general formula is $Ax+By+Cz+D=0$, which

$$A = \begin{vmatrix} y_2 - y_1 & z_2 - z_1 \\ y_3 - y_1 & z_3 - z_1 \end{vmatrix} \quad B = \begin{vmatrix} z_2 - z_1 & x_2 - x_1 \\ z_3 - z_1 & x_3 - x_1 \end{vmatrix} \quad C = \begin{vmatrix} x_2 - x_1 & y_2 - y_1 \\ x_3 - x_1 & y_3 - y_1 \end{vmatrix}$$

Divided $\sqrt{A^2 + B^2 + C^2}$ can be obtained a normal vector style

$$x\cos\alpha + y\cos\beta + z\cos\gamma - p = 0 \quad . \tag{11}$$

where α, β, γ =direction angle of normal vector of plane.

Rotate the "sight triangle" to the horizontal, and then shift the horizontal to 0 elevation. Put other related surfaces into the similar transformation, and then examine the elevation coordinates of relevant points in triangle area . If the point is greater than 0 , it is the block point.

(1) General formulas of coordinate transformation. Assuming the direction cosine matrix of the new coordinate is $\begin{vmatrix} l_1 & l_2 & l_3 \\ m_1 & m_2 & m_3 \\ n_1 & n_2 & n_3 \end{vmatrix}$, the Formulation of rotate coordinate as follows:

$$\begin{vmatrix} x \\ y \\ z \end{vmatrix} = \begin{vmatrix} l_1 & l_2 & l_3 \\ m_1 & m_2 & m_3 \\ n_1 & n_2 & n_3 \end{vmatrix} \begin{vmatrix} X \\ Y \\ Z \end{vmatrix} \quad . \tag{12}$$

Rotate the "sight triangle" to the horizontal, the normal direction of horizontal is the OZ direction of the new coordinates. So (n_1,n_2,n_3) is the direction cosine. $n_1=\cos\alpha$,$n_2=\cos\beta$,n3=$\cos\gamma$.

(2) After transform the coordinates, each points in the sight triangle have the same Z coordinate, as Z_0, let Z-Z_0=Z.

(3) By the step of (1) and (2), can be obtained a new sight triangle($\Delta p_1 p_2 p_3$) and a new coordinate(X,Y,Z), then determine whether the projection points of the horizontal is in the $\Delta p_1 p_2 p_3$.

If the point in the $\Delta p_1 p_2 p_3$, it can't be the block point, on the reverse, according to the value of Z and Z_0 to determine the block point.

(4) Calculate the distance from sight point to the block point, the nearest distance in the Original "sight triangle" is the 3D ASD.

Highway Safety Evaluation Model Based on 3D ASD

3D ASD is a response of road alignment in persons' eyes, whose value is varied with road alignment on the driving direction. This paper is going to build up a new highway safety evaluation model to fit in with the characteristics of 3D ASD, according to the relationship between the value of 3D ASD and the distance value corresponding to the road design speed and the running speed.

Highway Engineering Technique Standard orders that stopping sight distance is expressed as SSD and its value is shown in [Table 1]. When the value of the driver's 3D ASD arrives at the limit as 600m, the valid sight distance of present calculating spot is defaulted as 600m.

Table 1　SSD of all highway levels

Level	Free way，First class way，				Second，Third，Fourth way				
Design speed/(kmh^{-1})	120	100	80	60	80	60	40	30	20
SSD/(m)	210	160	110	75	110	75	40	30	20

Thus the highway safety evaluation model based on 3D ASD as a evaluation index is gained, shown in [Table 2].

Table 2　Standard of highway safety evaluation model based on 3D ASD

Evaluation	Security level	Notes
3D ASD=600m	good	Same V_{85}
SSD<3D ASD<600m	fair	Same V_{85}
3D ASD<SSD	poor	Same V_{85}

The evaluation procedure is shown in Fig.2.

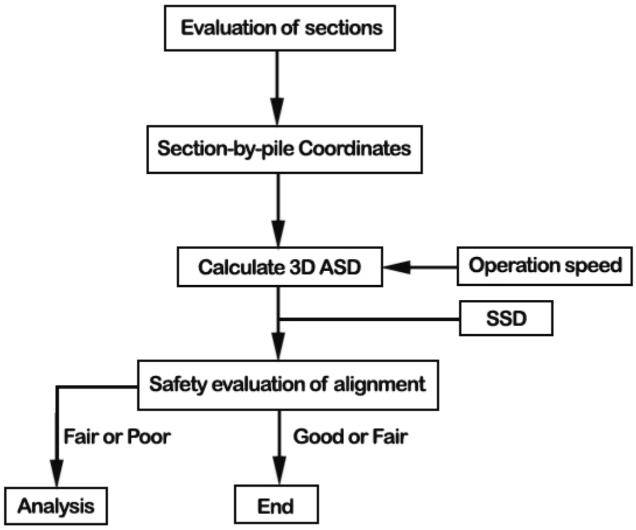

Fig.2 Chat of road traffic safety evaluation flow based on 3D ASD

Engineering Application

There is a new bi directional and four lane highway, of which the design speed is 100km/h and the subgrade width is 24.5m. According to the design information of the highway from K8+400 to K19+300, the 3D coordinate and the 3D ASD pile by pile are calculated by use of equal pile distance. The result is shown in Fig.3.

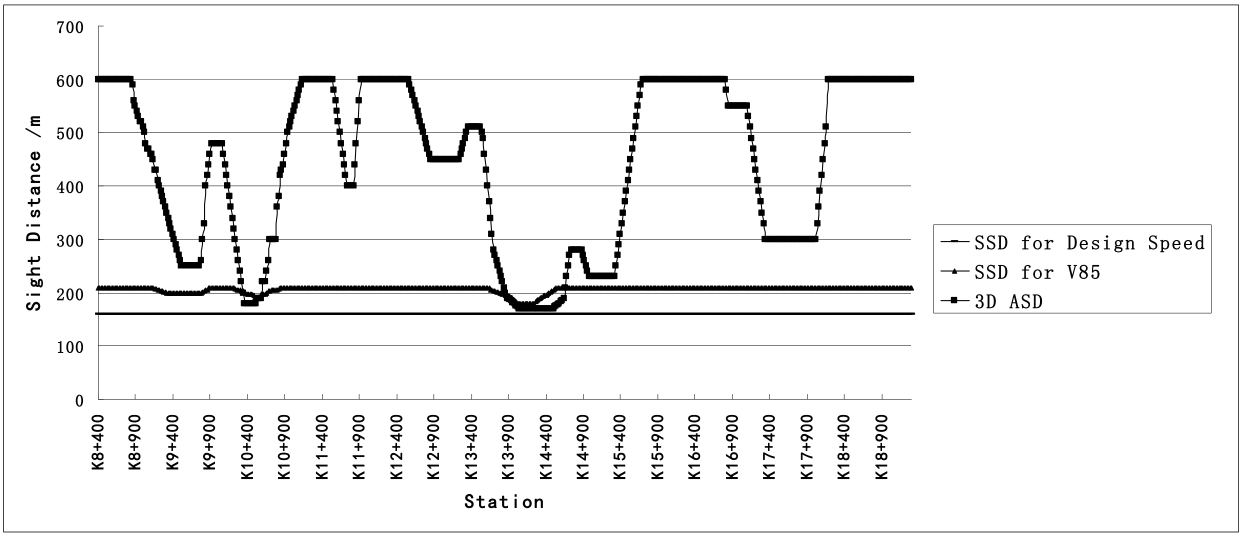

Fig.3 Sight distance of K8+400~K19+300

From the result of the highway safety evaluation, the conclusion is that the safety levels from K10+060 to K10+680 and from K13+450 to K14+810 are poor, the safety levels from K8+400 to K9+020, from K10+980 to K11+480, from K12+010 to K12+470 and from K15+730 to K16+880 are good, and the rest are fair. The evaluation results are basically the same as the analysis results of *Safety Evaluation Guide in Highway Project* and the past evaluation experience.

Conclusion

This paper presents a mathematic model for evaluating 3D ASD. The model is based on a parametric representation of the roadway and roadside features. The model is considered more flexible in modeling complex alignment geometry. The central objective of the model is to find an object location that connects the driver with a sight triangle to any roadside or roadway surface. The search method used in this paper is essentially a scan of the surface beneath the face of sight.

This 3D ASD model based on visual information will be one of the effective research tools in the field of road safety research, road safety audit, alignment assessment, accident black-pot discrimination and accident cause analysis etc. Hopefully, the method presented in this paper might bring some inspiration to other researchers.

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