Three-Dimensional Analysis of Sight Distance on Interchange Connectors

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The design of interchange ramps and connectors, especially in large freeway-to-freeway interchanges, involves the use of stopping sight distance (SSD) criteria to determine horizontal and vertical geometries. Long connectors are usually required to avoid difficult horizontal and vertical obstructions. Therefore the use of minimum design standards for both horizontal and vertical geometries is quite common. The results of an investigation that evaluated SSD on interchange connectors by computerized three-dimensional (3-D) models are documented. Interchange connector models were developed by using combinations of minimal horizontal and vertical geometries with a longitudinal traffic barrier and a cross slope. A graphical procedure was used to measure SSD in a 3-D environment. The results revealed that the 3-D method of measuring SSD was not significantly different from the conventional two-dimensional method of measuring SSD. When all the 3-D models were rotated and viewed from different angles, the line of sight was always obstructed by the longitudinal barrier. Driver perspective views revealed that the cross slope affected the available SSD significantly. Therefore when a vertical curve is combined with a horizontal curve that requires a cross slope, the line of sight is not blocked by the roadway surface. This observation indicates an additional conservatism in the current crest vertical curve methodology. Designers should consider using computerized 3-D models in their normal design procedures. The use of models will allow designers to view different geometric configurations before deciding on the final combination. The models will allow designers to see the end result before the actual construction begins and thereby possibly eliminate costly field alterations.

The design of ramps and connectors is critical to the successful operation of a directional interchange. Direct connectors are usually long and geometrically complicated to avoid horizontal and vertical obstructions. Therefore, sight distance plays a critical role in the determination of a safe design. Typically designers develop horizontal and vertical geometries independently of one another on the basis of AASHTO sight distance requirements (*1*). When conservative values are used, the concern for the effect of their combination on sight distance is not generally an issue. With ever increasing traffic volumes and construction costs, a better understanding of the interactive effects of horizontal and vertical alignments on sight distance is needed to provide designers with the tools required to evaluate a variety of tight geometric combinations.

PROBLEM STATEMENT

Sight distance is the most basic and critical element of highway design. It controls all aspects of design from the establishment of alignments to the development of the cross-section elements of the roadway (*2*). AASHTO generally describes sight distance as the length of roadway ahead visible to the driver. Most designers use values greater than the minimum described by AASHTO. However, interchanges provide the designer with an interesting challenge of providing the maximum amount of sight distance while using minimum design values of horizontal and vertical geometries in combination.

According to AASHTO, horizontal and vertical alignments should complement each other to improve appearance and encourage uniform speed; however, poorly designed combinations can spoil the good points and aggravate the deficiencies of each (*1*). Designers have historically been trained to develop horizontal and vertical alignments independently. They must then depend on their ability to envision the roadway in perspective on the basis of the plan and profile views of the roadway (*3*). Therefore the task of producing complementary alignments should be assigned to designers with many years of experience. However, experience alone does not guarantee the most appropriate alignment combination.

The effect of inadequate stopping sight distance (SSD) on horizontal curves with minimum shoulder widths along longitudinal concrete traffic barriers is another area of concern for designers. According to a 1989 study by Leisch (*4*), SSD is not provided when curvature exceeds approximately 50 to 70 percent of the maximum curvature for a specified design speed on a roadway with 3.05-m (10-ft) shoulders. The paper by Leisch documented the results of a study that evaluated the effect of AASHTO Figure III-26A on horizontal sight distance in freeway and interchange reconstruction. Inadequate lateral offset of longitudinal concrete traffic barriers appears to be a common problem on interchange connectors. The problem is also compounded when severe crest vertical curves are also present.

AASHTO describes SSD as the minimum sight distance available on a roadway that would enable a below-average operator to stop a vehicle traveling at or near the design speed before reaching a stationary object in its path. AASHTO developed a model for determining the minimum amount of SSD based on the sum of the distance traveled by the vehicle during the perception-reaction time and the distance traveled during braking. The following equation is used to calculate SSD:

$$S = 1.47 * t_{pr} * V + \frac{V^2}{30(f + G)} \quad (1)$$

where

S = SSD (ft),
t_{pr} = perception-reaction time (sec),
V = vehicle operating speed (mph),
f = coefficient of tire-pavement friction, and
G = roadway grade (decimal, + for upgrade, − for downgrade).

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AASHTO also describes sight distance as the distance along a roadway that an object of specified height is continuously visible to the driver. To measure this distance, three more parameters are required: (a) height of the driver's eye above the roadway surface, (b) the specified object height above the roadway surface, and (c) the height of the sight obstruction within the line of sight.

This methodology, which was formally introduced by AASHO in 1940, represented a significant change from the previous practice. The model introduced the concept of a small object [101.60-mm (4-in.)-high object] as the feature in the roadway rather than providing sight distance for the driver to see other vehicles in sufficient time to avoid them. Even though the model has remained the same, the parameters have shown a continuous change toward safer values. For example the driver eye height has been reduced to 1.07 m (3.5 ft) from the original 1.37 m (4.5 ft), and the pavement frictional values have been reduced approximately 70 percent (*5*). The assumed perception-reaction time is the only value that has remained constant from the original 1940 values.

DESIGN APPROACH

The design of highways has always been recognized as a three-dimensional (3-D) problem. Unfortunately, the current approach in determining horizontal alignments independently of vertical alignments requires designers to develop 3-D pictures in their minds simply by viewing two-dimensional (2-D) plans (plans, profiles, and cross sections). Although many experienced designers have no difficulty in visualizing an interchange from a 2-D drawing, problems arise when less experienced people have the design responsibility (*6*).

Computer-generated perspective plots have been used for a number of years to assist designers in visualizing details in the roadway. In 1968, Geissler (*3*) developed a computer program that developed perspective movies by feeding 3-D coordinates of terrain points into the computer and transforming them at desired intervals into perspective drawings that were finally photographed. In the same year, Park et al. (*7*) also developed a computer algorithm that plotted perspective views from the driver's eye by using design information as the data. This was the first attempt to develop 3-D perspectives from the driver's viewpoint. However, the process was very expensive because of the computer time and the amount of plotting required.

AASHTO's recommended method for developing good alignment coordination does not offer any quantitative criteria. Designers, experienced or not, must rely on their judgments in determining appropriate combinations of minimum horizontal and vertical alignment values. Although they are not recommended for interchanges, the use of near-minimum design values is common practice for connectors because of the limited availability of right-of-way and soaring construction costs. This paper attempts to provide insight into the effect of sight distance when using minimum design values of horizontal and vertical geometries in combination (*8*).

STUDY DESIGN

A typical one-lane bridge connector was developed and investigated for available sight distance. The focus of this paper was on the geometry of the horizontal and vertical alignment features in addition to the cross-section elements of the connector. The typical bridge connector was developed with a 3.66-m (12-ft) travel lane, a 1.22-m (4-ft) left shoulder, and a 2.44-m (8-ft) right shoulder. The Texas design manual (*9*) recommends a minimum 4.27-m (14-ft) travel lane for one-lane connectors with a minimum 1.22-m (4-ft) left shoulder. For sight distance evaluation, the critical issue was not the lane width but the distance from the centerline of the travel lane to the inside face of the barrier (*M*-lateral offset).

A test matrix, which included a range of values for the radius (*R*), the rate of change in vertical curvature (*K*) for the range of values of algebraic difference in grade (*A*), and the shoulder width (*M*-lateral offset), was developed to track any possible changes in the available sight distance. Table 1 lists the range of values for *R* based on *M* and AASHTO SSD values. The values of *M* ranged from 2.44 m (8 ft) to 5.49 m (18 ft) to cover as many possible combinations of lane and shoulder widths. The minimum 2.44-m (8-ft) value for *M* [0.61-m (2-ft) shoulder] was determined for those connectors constructed before the use of the criteria established in the Texas design manual. The 5.49-m (18-ft) value for *M* was chosen to be large enough to accommodate a 3.05-m (10-ft) shoulder adjacent to a 3.66-m (12-ft) travel lane. The listed radius (*R*) values were determined by using the following equation that relates the radius, the obstruction, the observer, and the object.

$$M = R\left[1 - \cos\left(\frac{90 * S}{\pi * R}\right)\right] = R\left[1 - \cos\left(\frac{28.65 * S}{R}\right)\right] \qquad (2)$$

where

M = middle ordinate of curve (ft),
R = radius of curve (ft), and
S = stopping sight distance (ft).

TABLE 1 Values of Minimum Radius on the Basis of *M* and SSD

M (m - ft)	40.23 km/h Design Speed (25 mph) 45.72 m SSD (150 ft)	56.32 km/h Design Speed (35 mph) 68.58 m SSD (225 ft)	72.42 km/h Design Speed (45 mph) 99.06 m SSD (325 ft)
2.44 - 8	106.68 - 350	240.79 - 790	502.62 - 1649
3.05 - 10	85.34 - 280	192.33 - 631	402.03 - 1319
4.27-14	60.66 - 199	137.16 - 450	286.82 - 941
5.49 - 18	51.82 - 170[a]	106.38 - 349	222.50 - 730

[a] Minimum Allowable Radius for e=0.08, M=4.96 m (16.27 ft)

The only exception to Table 1 was the *M* value of 5.49 m (18 ft) at a design speed of 40.23 km/hr (25 mph). According to Equation 2, this combination of *M* and SSD would equate to a radius of 46.68 m (153.152 ft). AASHTO requires the minimum radius for a design speed to be based on the maximum allowable side friction. Therefore according to AASHTO, the minimum allowable radius for a 40.23-km/hr (25-mph) design speed and a superelevation rate of 0.08 is 51.82 m (170.068 ft). By using Equation 2, this results in an *M* value of 4.96 m (16.27 ft). This relationship indicates that, for a design speed of 40.23 km/hr (25 mph), a superelevation rate of 0.08, and an *M* value of greater than 4.96 m, the minimum radius based on the side friction rather than the minimum radius based on SSD controls the design. A superelevation rate of 0.08 was used for all models because it is the recommended maximum allowed by the Texas design manual.

A total of 48 different 3-D computerized models were developed by using an interactive computer program on an Intergraph 225 MicroStation workstation and by using a software program called InRoads (*10*). The software program developed 3-D files on the basis of operator-developed alignment geometry and roadway surface templates to develop digital terrain models (DTMs) of the natural ground and the proposed connector surface. The DTM consisted of *x*, *y*, and *z* coordinates that were connected into 3-D triangular planes by using an algorithm known as Delauney's criterion. This criterion determined the smallest or most logical triangular surface on the basis of operator qualifiers (*10*).

The crest vertical curve lengths for all of the models were placed within the limits of the PC and the PT of the horizontal curve. The models were also developed with a vertical face longitudinal barrier on both sides of the roadway surface. This would simplify the location of conflict when determining the obstruction (roadway surface or barrier) hindering the line of sight. It was assumed that this combination would create the most complex geometric configuration.

The Intergraph 225 MicroStation workstation allowed the operator to develop perspective views of the 3-D models from any desired location. For each model a line was placed from the location representing the driver's eye [1.07 m (3.5 ft) above the roadway surface] and the object [152.4 mm (6 in. high)]. The models were then viewed from the top, the side, and then the driver's perspective looking at the object. From these views the operator was able to determine the obstruction impeding the line of sight.

The models were also used to calculate *x*, *y*, and *z* coordinates along the center of the travel lane. The distance between each coordinate was then calculated and summed by using a spreadsheet program. The summed distance thus represented the actual 3-D measurement of SSD along the roadway, which was then compared with the required 2-D SSD, which was measured on a flat horizontal plane.

RESULTS AND FINDINGS

Model Development

For the present study 12 independent horizontal alignments were developed to generate the 48 computer models. A typical alignment consisted of two tangent sections with a beginning point, a middle PI point, and an ending point. The same *x* and *y* coordinates were used to locate the beginning of the alignment, the PI, and the ending point for each alignment. The only difference in the alignments was the radius of the horizontal curve located at the PI, which was obtained from the required radius values in Table 1. A deflection angle of 90 degrees was also assumed for the horizontal alignments. The beginning station for the alignments was set at station 10+00; however, the ending station varied depending on the radius of the horizontal curve used..

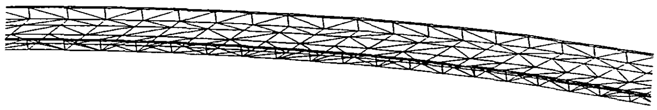

FIGURE 1 Isometric plot of typical 3-D computer model.

For each horizontal alignment four different vertical alignments were developed to correspond to *A* values of 8, 10, 12, and 14. Each vertical alignment contained an approach grade of 6 percent and descending grade that varied from 2 to 8 percent. The minimum vertical curve length was calculated by using the minimum *K* value for the appropriate design speed.

Each model was generated with *x*, *y*, and *z* coordinate points along the ridgeline established by the cross-sectional template. These ridgelines were located at the center of the travel lane, at the outside edge of the travel lane, at the edge of the shoulder or face of the barrier, and at the two top corners of the barrier, which are located 863.60 mm (34 in.) above the roadway surface. Transverse ridgelines were constructed at 3.05-m (10-ft) intervals starting at station 10+00 and continuing until the end of the vertical alignment. The 3.05-m (10-ft) interval was chosen to describe the connector as accurately as possible without consuming excessive amounts of computer memory. Figure 1 shows an isometric plot of a typical 3-D computer-generated wire-frame model developed for the study.

Sight Distance Evaluation

The location of the driver's eye and object was based on the location of the vertical curve. The purpose was to place the driver's eye and object location inside both the vertical and horizontal curves. Since the vertical alignments were designed with symmetric parabolic curves, the driver's eye and object were placed equal distances from the vertical PI station.

Figure 2 is a 3-D plot of a connector from the perspective of the driver. The computer camera position was located at the driv-

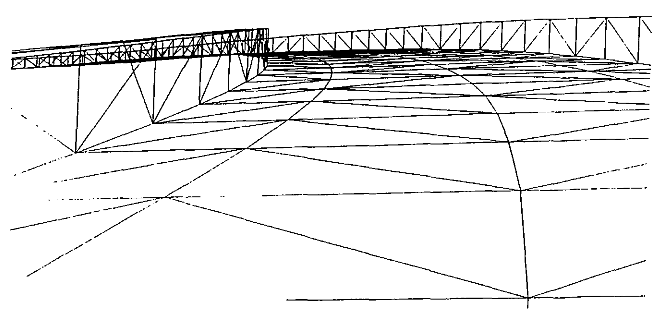

FIGURE 2 3-D plot of driver's perspective view.

er's eye height of 1.07 m (3.5 ft) above the road surface and was directed along the line of sight toward the 152.4-mm (6-in.)-high object location. The expectation from this perspective view was that the critical point along the line of sight would be a point where the barrier and the pavement surfaces meet. This would indicate that both the horizontal and vertical alignments are the design controls for that particular combination of K, A, R, and M. What became obvious after reviewing all the models from the driver's perspective was that the line of sight was obstructed only by the barrier and not the roadway surface. The controlling feature thus became the barrier and not the roadway surface. This would indicate that when the cross slope is also taken into consideration, the horizontal alignment becomes the controlling geometric feature for all combinations of minimum horizontal and vertical curvatures.

Another interesting observation from these perspective views was that the roadway surface was visible from beginning to end along the line of sight. This was due to the influence of a favorable cross slope that increased the length of roadway surface visible to the driver because it both lowered the roadway surface elevation along the line of sight and tilted the roadway surface so that it faced the driver. Again what was expected was that a portion of the roadway surface would not be visible to the driver. From a traditional 2-D plot of a vertical alignment (profile view), a portion of the pavement is not visible to the driver because the end of the line of sight is 152.4 mm (6 in.) above the roadway surface. To confirm this situation two separate graphs were developed and compared. The top plot in Figure 3 was developed by plotting surface elevation points along the center of the travel lane (the horizontal curve) from the point of the driver's eye to the object location. The results indicate a 2-D relationship in which a portion of the roadway surface is not visible to the driver. The bottom plot in Figure 3 was developed by plotting the surface elevation points along the line of sight. The plot clearly shows that the line of sight is not obstructed by the roadway surface.

The question that needs to be answered is, What is the minimum vertical curve length that produces the situation in which the line of sight is also obstructed by the roadway surface? To answer this, the study investigated less than minimum vertical curve lengths in which the line of sight intersects the point where the barrier meets the roadway surface. This would produce vertical curve lengths less than the minimum recommended by AASHTO.

The procedure for determining the minimum 3-D vertical curve length consisted of making incremental reductions in the minimum 2-D vertical curve length and then plotting the surface elevation along the line of sight, in addition to plotting a line representing the line of sight. The vertical curve length that produced the situation in which the roadway surface blocked the line of sight was considered the minimum 3-D vertical curve length. Figure 4 is a series of graphs that show plots of the surface elevations along the lines of sight (solid lines) and lines representing the lines of sight (dashed lines) for different values of vertical curve length. This graphical procedure was repeated for all combinations of K, R, and M. For clarification the absolute minimum vertical curve length is described as the 3-D vertical curve length, whereas the minimum vertical curve length required by K values is described as the 2-D vertical curve length.

The results of this procedure are listed in Table 2 for a design speed of 72.42 km/hr (45 mph). Table 2 lists the 2-D vertical curve values, 3-D vertical curve values for a cross slope of 0.08, and 3-D vertical curve values for a cross slope of 0.06. The results indicate that the cross slope and horizontal offset (M value) have a significant effect on the absolute minimum vertical curve length. They also indicate that the 3-D vertical curve lengths are significantly smaller than the conventional 2-D vertical curve lengths. For example, a cross slope of 0.08 and an M value of 2.44 m (8 ft) produces 3-D vertical curve lengths approximately 28 percent less than the 2-D vertical curve lengths for a design speed of 72.42 km/hr (45 mph) and all values of A. In addition for a cross slope of 0.08 and an M value of 5.49 m (18 ft), the 3-D vertical curve length is approximately 46 percent less than the required 2-D vertical curve length for a design speed of 72.42 km/hr (45 mph). The results for a cross slope of 0.06 were slightly less than the results for a cross slope of 0.08.

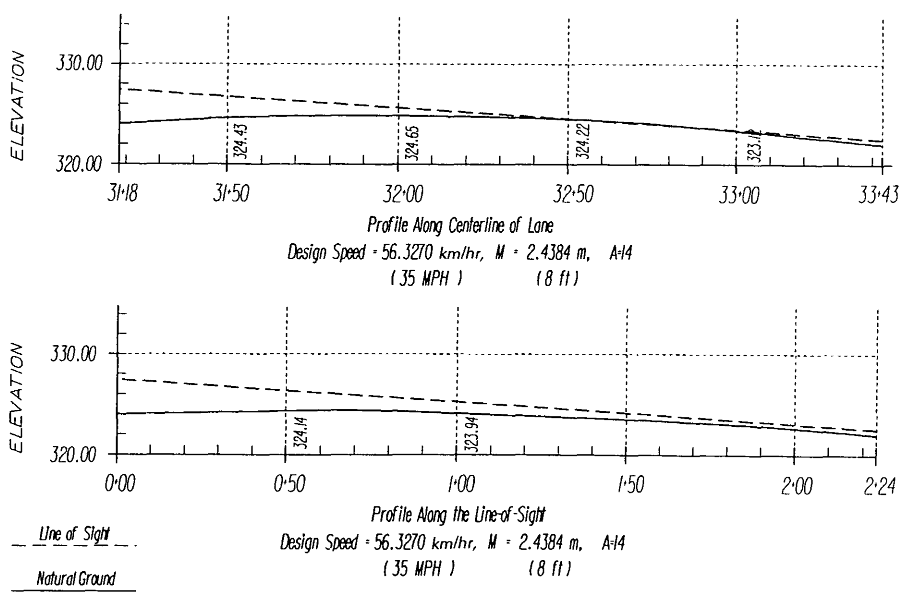

FIGURE 3 Profile plots.

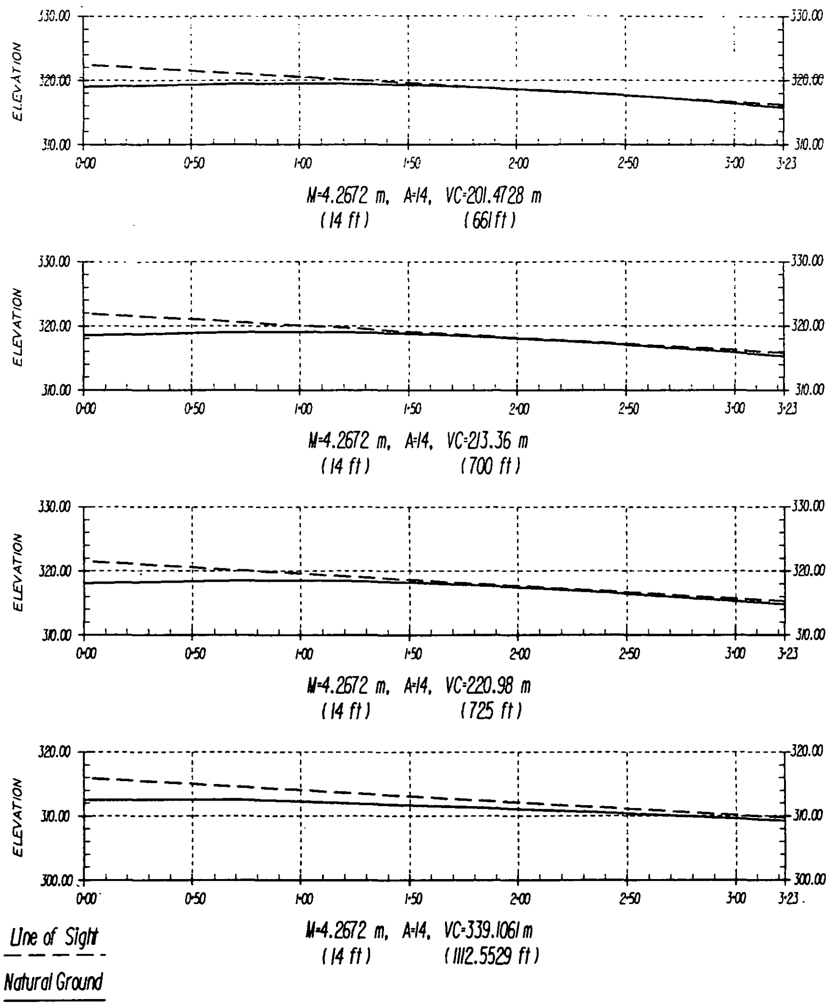

FIGURE 4 Profile plots with incremental reductions in vertical curve lengths.

3-D Measurement of SSD

The purpose of making a 3-D measurement of SSD was to determine if there is a significant difference in the current procedure for determining SSD measured in the 2-D horizontal plane (x and y coordinates only) and the actual 3-D distance between the driver's eye and the object. The conventional approach to determining the available SSD is to consider the horizontal and vertical geometries separately. The horizontal SSD is determined from the 2-D plan view. This means that only the horizontal alignment (x and y coordinates) is considered. The vertical SSD is determined from the profile view, in which only the station and elevation (x and y coordinates) are considered. The approach in this paper for measuring 3-D SSD consisted of calculating x, y, and z coordinates along the alignment (center of the travel lane) in increments of 0.08 m (0.25 ft). For this procedure a large number of coordinate points were developed to increase the accuracy of measurement. For example the 72.42-km/hr (45-mph) design speed criteria requires an SSD value of 99.06 m (325 ft). In increments of 0.08 m (0.25 ft), this results in 1,300 individual coordinate points that were used to calculate the 3-D distance. A spreadsheet was used to sum the distance between each point. This result was then compared with the horizontal measure of SSD that only considers the x and y coordinates. Table 3, which lists the results, indicates that the difference between 2-D and 3-D SSDs is very small. The largest difference was only 29.96 mm (0.0983 ft). What must be noted is that the 3-D measurement occurred in the area of the vertical curve and not on a vertical tangent grade. This situation minimizes the difference in 2-D and 3-D measurements. Another interesting observation is that as the vertical curve length increases, the difference between the 2-D and the 3-D measurements decreases. This is because the driver's eye and object were located within the vertical curve and the elevation difference between each point decreases as the vertical curve length increases.

The differences in 2-D and 3-D measurements were also examined on a vertical tangent grade. Measurement on a vertical tangent grade produced the most significant difference in SSD because of the lengths of roadway surface measured in the 2-D and 3-D environments. The 3-D approach to measurement consisted of measuring the actual roadway surface along the center of the travel lane, whereas the 2-D approach measured the length of roadway projected on a horizontal plane. For this analysis a range of grades from 2 to 8 percent was chosen because they presented the most commonly used grades in the design of a road-

TABLE 2 Values of 3-D Vertical Curve Lengths

Algebraic Difference (%)	M (m)	2-D Min. VC (m)	X-Slope = 0.08 3-D Min. VC (m)	X-Slope = 0.08 % Decrease	X-Slope = 0.06 3-D Min. VC (m)	X-Slope = 0.06 % Decrease
A=14	2.44	339.11	244.14	28.0	262.44	22.6
	3.05	339.11	228.30	32.7	248.41	26.7
	4.27	339.11	201.47	40.6	224.03	33.9
	5.49	339.11	180.14	46.9	203.61	40.0
A=12	2.44	290.66	209.70	27.9	225.25	22.5
	3.05	290.66	195.99	32.6	213.06	26.7
	4.27	290.66	173.13	40.4	192.33	33.8
	5.49	290.66	155.14	46.6	175.26	39.7
A=10	2.44	242.20	174.96	27.8	187.76	22.5
	3.05	242.20	163.37	32.5	178.00	26.5
	4.27	242.20	144.78	40.2	160.93	33.6
	5.49	242.20	129.84	46.4	146.61	39.5
A=8	2.44	193.77	139.90	27.8	150.57	22.3
	3.05	193.77	131.06	32.4	142.65	26.4
	4.27	193.77	116.13	40.1	128.93	33.5
	5.49	193.77	104.24	46.2	117.96	39.1

way. Table 4 shows the results for design speeds of 40.23 km/hr (25 mph), 56.32 km/hr (35 mph), and 72.42 km/hr (45 mph). The results also revealed that as the grade increased the difference in the 2-D and the 3-D measurements also increased. These results, when compared with those in Table 3, were significantly higher for tangent grades of greater than 5 percent. The difference in comparison with the overall value of SSD was extremely small, however.

CONCLUSIONS AND RECOMMENDATIONS

Summary

The results of the graphical procedure demonstrated that the roadway feature blocking the line of sight was the longitudinal barrier for all 48 computer-generated 3-D models. This indicated that the horizontal alignment (radius and offset distances) was the con-

TABLE 3 3-D Measurement of SSD on Crest Vertical Curve

Algebraic Difference (%)	40.23 km/h Design Speed (25 mph) M (m)	SSD (m)	3-D Measure (m)	56.32 km/h Design Speed (35 mph) M (m)	SSD (m)	3-D Measure (m)	72.42 km/h Design Speed (45 mph) M (m)	SSD (m)	3-D Measure (m)
8	2.44	45.72	45.75	2.44	68.58	68.60	2.44	99.06	99.09
10	2.44	45.72	45.74	2.44	68.58	68.59	2.44	99.06	99.07
12	2.44	45.72	45.74	2.44	68.58	68.59	2.44	99.06	99.07
14	2.44	45.72	45.74	2.44	68.58	68.59	2.44	99.06	99.07
8	3.05	45.72	45.75	3.05	68.58	68.60	3.05	99.06	99.09
10	3.05	45.72	45.74	3.05	68.58	68.59	3.05	99.06	99.07
12	3.05	45.72	45.74	3.05	68.58	68.59	3.05	99.06	99.07
14	3.05	45.72	45.74	3.05	68.58	68.59	3.05	99.06	99.07
8	4.27	45.72	45.75	4.27	68.58	68.60	4.27	99.06	99.09
10	4.27	45.72	45.74	4.27	68.58	68.59	4.27	99.06	99.07
12	4.27	45.72	45.74	4.27	68.58	68.59	4.27	99.06	99.07
14	4.27	45.72	45.74	4.27	68.58	68.59	4.27	99.06	99.07
8	4.96	45.72	45.75	5.49	68.58	68.60	5.49	99.06	99.09
10	4.96	45.72	45.74	5.49	68.58	68.59	5.49	99.06	99.07
12	4.96	45.72	45.74	5.49	68.58	68.59	5.49	99.06	99.07
14	4.96	45.72	45.74	5.49	68.58	68.59	5.49	99.06	99.07

TABLE 4 3-D Measurement of SSD on Vertical Tangent Grade

	40.23 km/h Design Speed (25 mph)		56.32 km/h Design Speed (35 mph)		72.42 km/h Design Speed (45 mph)	
Tangent Grade (%)	SSD (m)	Actual Distance (m)	SSD (m)	Actual Distance (m)	SSD (m)	Actual Distance (m)
2	45.72	45.73	68.58	68.59	99.06	99.08
3	45.72	45.74	68.58	68.61	99.06	99.11
4	45.72	45.76	68.58	68.63	99.06	99.14
5	45.72	45.78	68.58	68.67	99.06	99.18
6	45.72	45.80	68.58	68.70	99.06	99.24
7	45.72	45.83	68.58	68.75	99.06	99.30
8	45.72	45.87	68.58	68.80	99.06	99.38

trolling geometric feature of the interchange connectors, even though the vertical alignment was designed with the same design speed criteria. In general, when evaluating geometric combinations that contain severe horizontal and crest vertical curve combinations, the horizontal alignment of the connector will probably be the controlling geometric feature. If this is the case, as long as the vertical alignment is designed with K values equal to or greater than the design speed of the horizontal alignment, the horizontal feature will control the available SSD. These results also demonstrate the importance of determining the available SSD for both the horizontal and the vertical alignments before concluding the design speed of the connector.

As previously stated the current design standards were developed by assuming a 152.4-mm (6-in.) object height and a 1.07-m (3.5-ft) driver eye height. On the basis of this definition, AASHTO developed a methodology for calculating minimum crest vertical curve lengths that uses the roadway surface as the feature that obstructs the line of sight. This methodology considers sight distance as the only criterion for determining minimum crest vertical curve length. The methodology was developed by using 2-D criteria (considering only the elevation and distance along the center of the travel lane), which limits the application to locations where a crest vertical curve is combined with a horizontal curve that does not require a cross slope. In actual design this situation is only applicable to a combination of a crest vertical curve with a straight horizontal alignment.

The results of the present study clearly indicate that when a crest vertical curve is combined with a horizontal curve that requires a cross slope, the roadway surface does not block the line of sight. Significant reductions in vertical curve lengths are possible when viewed from the perspective of only providing the minimum amount of sight distance. Reductions as small as 28 percent for M = 2.44 m (8 ft) and as large as 46.2 percent for M = 5.49 m (18 ft) are possible for a design speed of 72.42 km/hr (45 mph). These results, if used in design, would violate the vertical alignment design standards recommended by AASHTO. However according to the procedure for measurement described by AASHTO, the results would not violate SSD guidelines because the 152.4-mm (6-in.) object would continue to be visible to the driver.

By using the current 2-D methodology for determining minimum crest vertical curve lengths, the results also indicated that the design of a crest vertical curve when combined with a horizontal curve that requires a cross slope is more conservative because of the additional available vertical sight distance. For the models developed in the present study, in which the minimum vertical curvature is combined with the minimum horizontal curvature, the additional vertical sight distance was limited because of the lateral obstruction. This would indicate that the design of a roadway with a higher horizontal design speed than a vertical design speed will result in a measurable vertical sight distance that is longer than the sight distance calculated by using the 2-D vertical design equations. The additional available vertical sight distance constitutes an amount not realized in the current crest vertical curve methodology.

Recommendations

The results indicate that significant reductions in vertical curvature are possible if one is designing a roadway solely on the basis of providing the minimum amount of sight distance. However a design made solely from this perspective may lead to other unexpected problems. Design consistency would be one potential problem area because each geometric combination would produce unique driving conditions. Drivers would be required to drive solely on their visual capabilities. They would also be required to expect a sharper crest vertical curve when a cross slope is introduced.

These new lower crest vertical curve lengths should also be investigated from the perspective of driver discomfort. Caution should be used in incorporating the lower values because they may produce an unacceptable level of driver discomfort. It is strongly recommended that designers use values that are equal to or exceed AASHTO's lower-range values for crest vertical curve lengths. According to the Texas design manual, "Greater than minimum SSD should normally be used and minimum values used only in select instances where economic or other restrictive conditions dictate" (*9*). The point of using greater than minimum values by reclassifying AASHTO's lower-range values as minimum values and the upper-range values as desirable values is also emphasized. The use of values equal to or greater than the minimum would also support AASHTO's recommendation of designing with "prevalent expectancies" because it is one of the most important ways to aid driver performance. AASHTO states that when drivers "do not get what they expect, or get what they do not expect, errors may result" (*1*). Additional research is needed to evaluate all of the ramifications associated with using values of crest vertical curvature less than the recommended minimum.

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