Sight Distance Models for Unsymmetrical Sag Curves

SAID M. EASA

Unsymmetrical sag (vertical) curves may be required at complex interchanges and other highway locations because of clearance and other controls. No relationships are available for designing or evaluating these curves on the basis of sight distance needs, so sight distance models for unsymmetrical sag curves are developed for headlight and overhead obstacle controls. For headlight control, the model relates the minimum sight distance (S_m), vertical curve parameters, and vehicle and object characteristics. For overhead control, the model relates the available sight distance, sag curve parameters, vertical clearance and location of overhead obstacle, and locations and heights of driver eye and object. A procedure for calculating S_m is presented. The distinct characteristics of sight distance on unsymmetrical sag curves are examined. To facilitate practical use, graphs and tables of the minimum sight distance for headlight and overhead controls are established. The length requirements and sight distance characteristics of symmetrical and unsymmetrical sag curves were found to be quite different. The developed models should be valuable in the evaluation of safety and operation of unsymmetrical sag curves.

The current AASHTO models for designing sag curves based on stopping sight distance (SSD) consider two cases: headlight control and overhead obstacle control (*1–4*). The headlight sight distance depends on the position of the headlights and the direction of the light beam. Generally, the headlight height is 2.0 ft and the upward divergence of the light beam from the longitudinal axis of the vehicle is 1 degree. The AASHTO model defines SSD as the distance between the eye of the driver and the point where the light beam intersects the road surface.

For overhead obstacle control, as in the case of a sag curve at an underpass, the structure may restrict the sight distance. The 1965 AASHO policy (*2*) presents formulas for checking the available sight distance or computing the required curve length assuming that the structure is centered over the vertical point of intersection (PVI). Derivation of these formulas can be found in work by Hickerson (*5*) and Ives and Kissam (*6*). The 1965 AASHO policy suggests a truck driver eye height of 6.0 ft and an object height of 1.5 ft, which may represent the vehicle taillight or a discernible portion of an oncoming vehicle. Olson et al. (*7*) evaluated the AASHO equations for a driver eye height of 9 ft, which is typical for cab-over-engine tractors, and an object height of 0.5 ft. They found that the resulting curves were about 10 percent longer than those found in the AASHO policy.

Sag curves are normally designed for headlight control based on SSD. The available sight distance at an undercrossing sag curve is then checked when special conditions exist; for example, at a two-lane undercrossing without ramps where passing sight distance (PSD) is desirable (*2*). In addition, at complex locations where information is difficult to perceive, the decision sight distance (DSD) should be provided. DSD values are presented in the AASHTO *Policy on Geometric Design of Highways and Streets* (Green Book) (*4*). Revised design values have been developed recently for SSD by Neuman (*8*) and Olson et al. (*7*); for PSD by Harwood and Glennon (*9*), based on a model by Glennon (*10*); and for DSD by Neuman (*8*) and McGee (*11*). A methodology for operational and cost-effectiveness analysis of locations with sight distance restriction has been presented by Neuman et al. (*12*) and Neuman and Glennon (*13*). The effects of sight distance on highway safety have been reviewed by Glennon (*14*).

Both the headlight and overhead control models assume that the sag curve is a symmetrical parabola whose tangents have equal horizontal projections. In some situations, such as at interchanges, an unsymmetrical curve may be required because of clearance or other design controls [AASHTO (*4*)]. The formulas for laying out unsymmetrical curves have been presented in a number of highway engineering texts (*5,15*); however, the available sight distance on these curves has not been addressed in the literature. Although the use of unsymmetrical curves in practice is infrequent, it is essential to ensure that they provide safe operations.

Sight distance models were developed for unsymmetrical sag curves for both headlight and overhead controls. For overhead control, the structure may lie at any point on the curve or tangent. The models can be used to design the required length of a new curve or to check the adequacy of the available sight distance on existing curves. A brief description of the unsymmetrical curve follows.

The unsymmetrical vertical curve consists of two parabolic arcs with a common tangent at the intersection point, PVI, of the initial and final tangents (Figure 1). The horizontal projections of the two arcs, which are unequal, are denoted by L_1 and L_2. The grades of these tangents are g_1 and g_2, respectively. The grade is positive if it is upward to the right and negative if it is downward to the right. The beginning point of the vertical curve (BVC) lies on the initial tangent with the adjacent arc designated as the first arc. The end point (EVC) lies on the final tangent with the adjacent arc designated as the second arc. The second arc represents the smaller arc. These vertical curve terminologies are used regardless of the travel direction. The rates of change in grade of the two parabolic arcs are given by Hickerson (*5*). Let the ratio of the length of the second arc to the length of the curve be denoted by R. That is,

Department of Civil Engineering, Lakehead University, Thunder Bay, Ontario, Canada P7B 5E1.

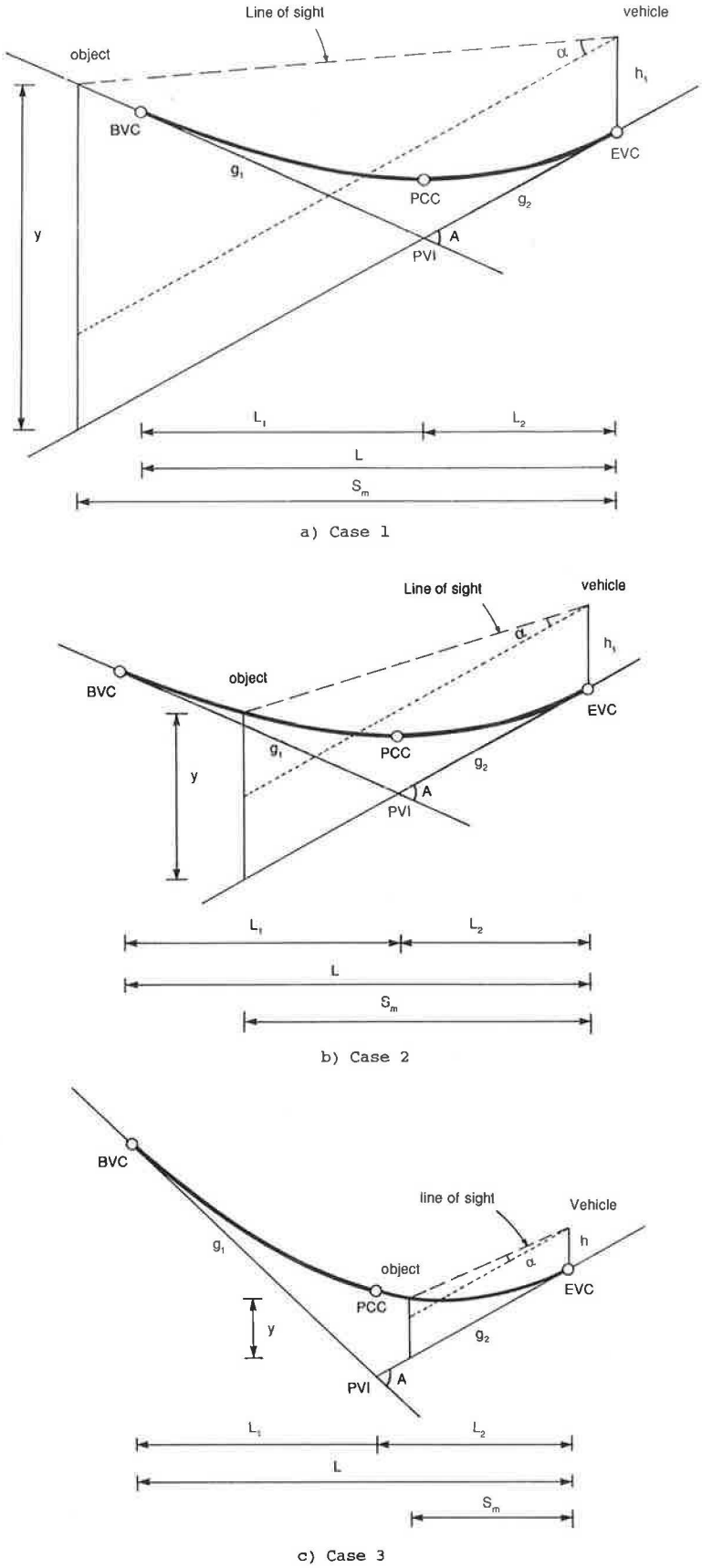

FIGURE 1 Geometry of sight distance for headlight control on an unsymmetrical sag curve.

$$R = L_2/L \quad (1)$$

Then, Hickerson's formulas for the rates of change in grade can be written in terms of R as follows:

$$r_1 = (A/L)R/(1 - R) \quad (2)$$

$$r_2 = (A/L)(1 - R)/R \quad (3)$$

where

r_1, r_2 = rates of change in grade of the first and second parabolic arcs, respectively,
A = algebraic difference in grades $(g_2 - g_1)$, and
L = length of the vertical curve.

For symmetrical curves, $L_1 = L_2$, R of Equation 1 equals 0.5, and Equations 2 and 3 yield equal rates of change in grade of A/L. The radius of vertical curvature (a measure of sharpness) equals the inverse of the rate of change in grade. Thus, for the unsymmetrical curve, the radius of the first and second arcs $K_1 = 1/r_1$ and $K_2 = 1/r_2$. The radius of vertical curvature of the symmetrical curve $K = 1/r = L/A$. Therefore, if L_2 is the smaller arc, the second arc will be sharper and the first arc will be flatter than a symmetrical curve with the same length. Note that the variables g_1, g_2, and A are assumed to be in decimals in the developed relationships.

HEADLIGHT CONTROL

The geometry of sight distance for headlight control on an unsymmetrical sag curve is shown in Figure 1. The critical direction of travel for headlight control is generally from the smaller to the longer arc. The minimum sight distance, S_m, occurs when the driver is at EVC. For some cases, however, S_m will be the same in both travel directions.

Geometric Relationships

Relationships for the minimum sight distance are developed for three cases:

- Case 1: Sight distance greater than curve length,
- Case 2: sight distance less than curve length but greater than length of the smaller arc, and
- Case 3: Sight distance less than length of the smaller arc.

In all cases, h_1 and α denote the headlight height and the upward divergence (in degrees) of the light beam from the longitudinal axis of the vehicle, respectively. The variable y is given by

$$y = h_1 + S_m \tan \alpha \quad (4)$$

Case 1: Sight Distance Greater Than Curve Length ($S_m \geq L$)

The geometry of Case 1 is shown in Figure 1a. The variable y is also written as

$$y = (S_m - L_2)A \quad (5)$$

Equating the right-hand sides of Equations 4 and 5 and substituting for L_2 from Equation 1 gives

$$L = (S_m/R) - (h_1 + S_m \tan\alpha)/RA \qquad S_m \geq L \quad (6)$$

Case 2: Sight Distance Less than Curve Length but Greater Than Length of Smaller Arc ($L_2 \leq S_m \leq L$)

The variable y in Figure 1b is written as

$$y = (S_m - L_2)A + r_1(L - S_m)^2/2 \quad (7)$$

Equating the right-hand sides of Equations 4 and 7 and substituting for L_2 and r_1 from Equations 1 and 2 gives

$$aL^2 + bL + c = 0 \quad (8)$$

where

$$a = (1 - 2R)RA \quad (9)$$

$$b = 2(1 - R)(h_1 + S_m \tan \alpha) - 2(1 - 2R)S_mA \quad (10)$$

$$c = -ARS_m^2 \quad (11)$$

The solution of Equation 8 is given by (considering the positive root)

$$L = [-b + (b^2 - 4ac)^{1/2}]/2a \qquad L_2 \leq S_m \leq L \quad (12)$$

Case 3: Sight Distance Less than Length of Smaller Arc ($S_m \leq L_2$)

The variable y in Figure 1c is written as

$$y = r_2S_m^2/2 \quad (13)$$

Equating the right-hand sides of Equations 4 and 13 and substituting for r_2 from Equation 3 gives

$$L = [(1 - R)/R]AS_m^2/2(h_1 + S_m \tan \alpha) \qquad S_m \leq L_2 \quad (14)$$

Comparison with Symmetrical Curves

For symmetrical sag curves, where $R = 0.5$, Equation 6 of Case 1 reduces to

$$L_s = 2S_m - 2(h_1 + S_m \tan \alpha)/A \qquad S_m \geq L_s \quad (15)$$

where L_s = length of the symmetrical curve. For Case 2, for $R = 0.5$, Equations 9–11 give $a = 0$, $b = h_1 + S_m \tan \alpha$, and $c = -0.5AS_m^2$. Substituting these variables into Equation 8 gives

$$L_s = AS_m^2/2(h_1 + S^m \tan \alpha) \qquad S_m \leq L_s \quad (16)$$

Equations 15 and 16 are the known formulas for symmetrical curves for $S_m \geq L_s$ and $S_m \leq L_s$, respectively (*6,16*). For Case 3, Equation 14 also reduces to Equation 16 for $R = 0.5$, as expected.

A comparison of the length requirements of symmetrical and unsymmetrical curves is shown in Figure 2. As noted, the ratio of the length of an unsymmetrical curve and that of a symmetrical curve (providing the same sight distance) is much greater than one for smaller values of R. The lower and upper bounds of this ratio are given by

$$(1/2R) \leq L/L_s \leq (1 - R)/R \tag{17}$$

The lower bound corresponds to Case 1 and the upper bound corresponds to Case 3.

Design Length Requirements

For headlight control, Figures 3 and 4 show the design length requirements of unsymmetrical sag curves for $R = 0.3$ and 0.4, respectively, based on SSD requirements of AASHTO. Figure 5, which is similar to that of AASHTO (*4*), shows the length requirements for symmetrical curves ($R = 0.5$). For other values of R, the length requirements can be interpolated from these figures. The vertical lines at the lower left of figures represent the minimum curve length, which equals three times the design speed in miles per hour. If the designer wishes to use other SSD design values [see, for example, Neuman (*8*)], the length requirements can be determined approximately from Figures 3–5. In this case, the speeds associated with the curves are ignored and the curve for the specified SSD value is interpolated using the adjacent curves.

There are drainage requirements for curbed pavements on symmetrical sag curves, whose first and second grades have different signs. The AASHTO policy requires a minimum grade of 0.3 percent at a point about 50 ft from the level point (*4*). This corresponds to a K value equal to 50/0.3 = 167. For unsymmetrical sag curves, the drainage requirements may be controlled by the first or second arc, depending on the location of the level point. The first arc controls if the level point lies on it, which occurs when the grade of the tangent at PCC is positive ($g_1 + r_1L_1 > 0$). The second arc controls if the grade of the tangent at PCC is negative ($g_1 + r_1L_1 < 0$).

When the first arc controls, K_1 equals 167. This yields a maximum curve length equal to 167 $AR/(1 - R)$, based on Equation 2. Similarly, when the second arc controls, K_2 equals 167 and the maximum curve length equals 167 $A(1 - R)/R$, based on Equation 3. These maximum values for drainage requirements are shown by dashed lines in Figures 3–5. All combinations above and to the left of the dashed line would satisfy the drainage criterion. For the combinations below and to the right of the line, pavement drainage must be carefully designed. For $R = 0.4$, for example, if the first arc controls, the maximum length for the drainage criterion is less than the minimum length for the headlight criterion for speeds of about 45 mph and greater. For symmetrical sag curves, the drainage criterion is not critical for almost all the speeds.

OVERHEAD OBSTACLE CONTROL

The geometry of sight distance for overhead control on an unsymmetrical sag curve is shown is Figure 6. Suppose that L_2 is smaller than L_1, so that the second arc is sharper. The

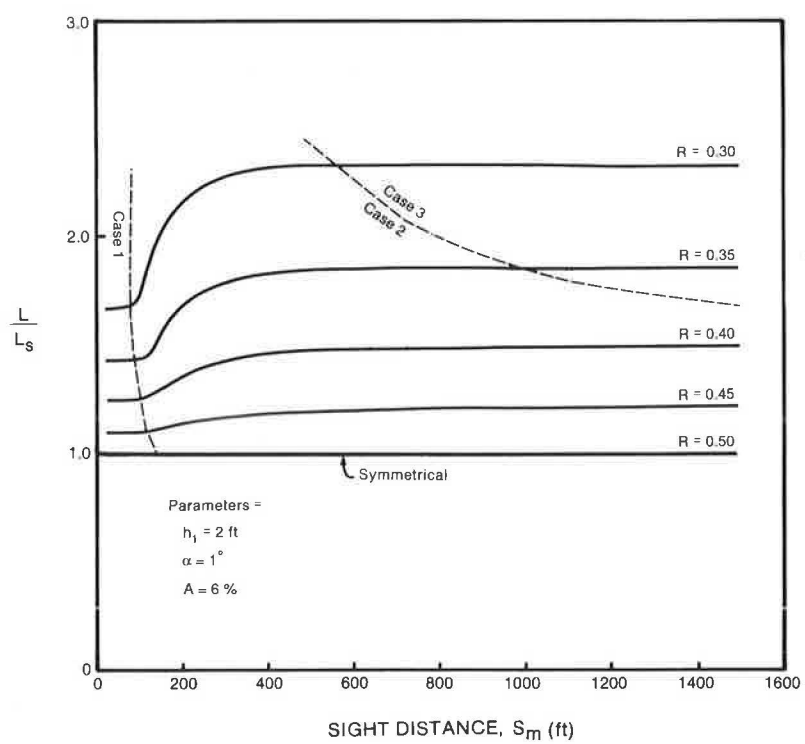

FIGURE 2 Comparison of symmetrical and unsymmetrical sag curves for headlight control.

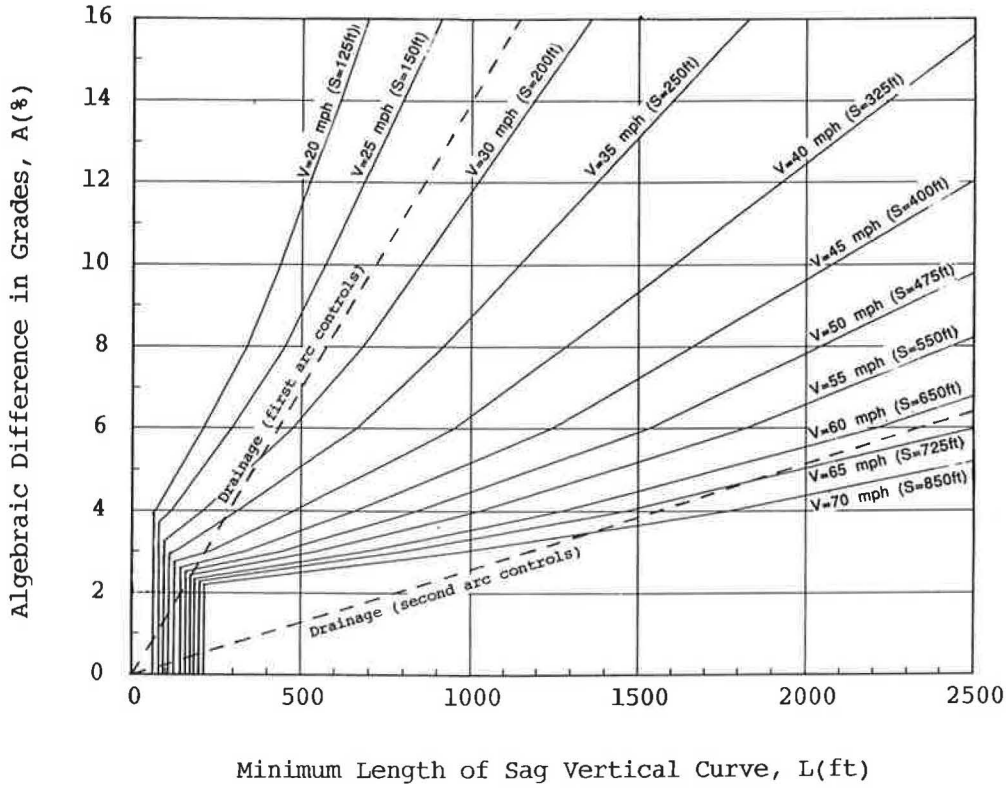

FIGURE 3 Design length requirements of unsymmetrical sag curves for headlight control (R = 0.3).

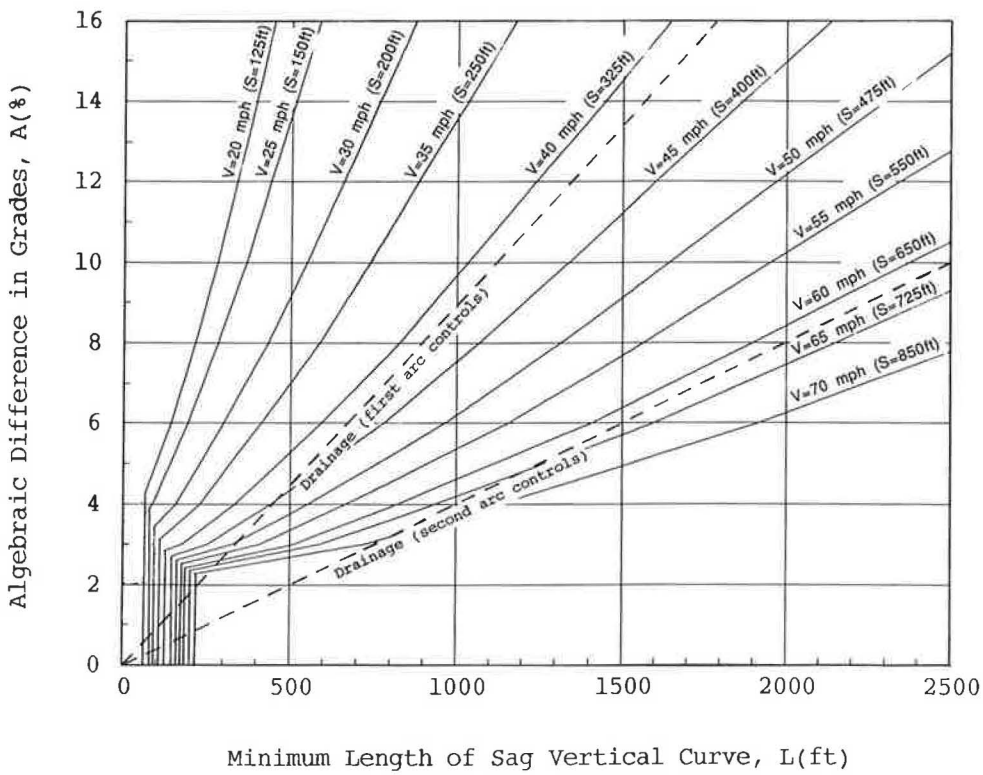

FIGURE 4 Design length requirements of unsymmetrical sag curves for headlight control (R = 0.4).

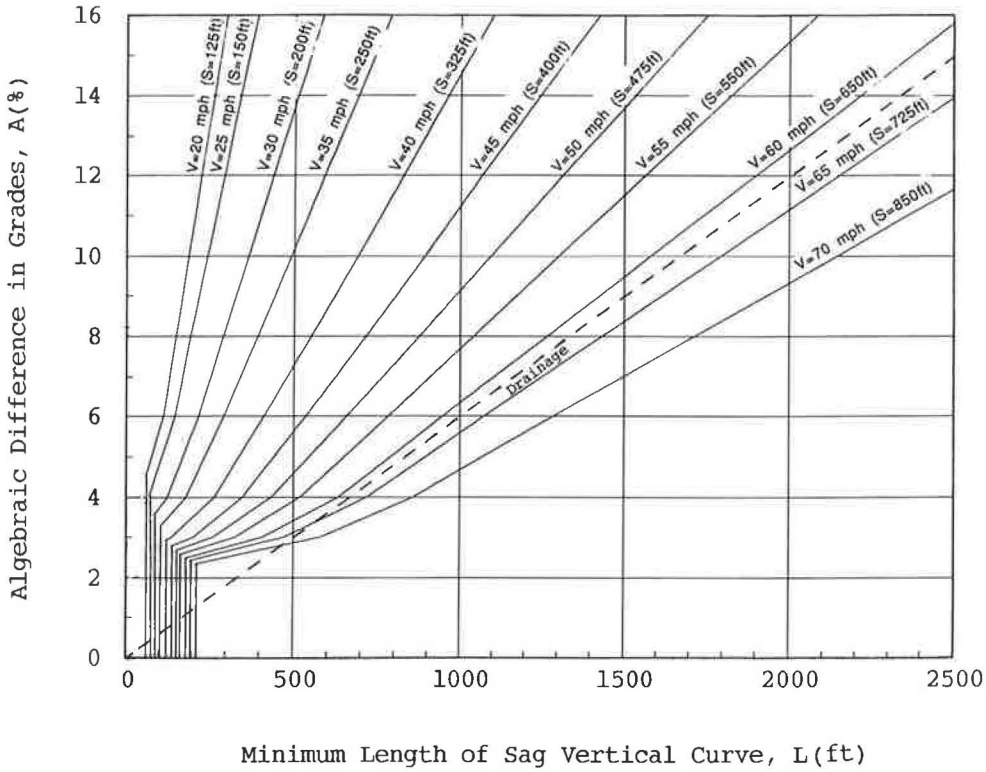

FIGURE 5 Design length requirements of symmetrical sag curves for headlight control (R = 0.5).

direction of travel with the minimum sight distance depends on the location of the obstacle, as will be shown later. Geometric relationships for the available sight distance are developed next, followed by a procedure for calculating the minimum sight distance and a comparison with symmetrical curves. In Figure 6, h_1 and h_2 may represent the driver eye or object height. However, to simplify the presentation these variables are considered to refer to the driver and object, respectively.

Geometric Relationships

Suppose for now that the overhead obstacle lies on the second arc or beyond EVC. The following six cases are considered:

- Case 1: Driver before BVC and object beyond EVC,
- Case 2: Driver before BVC and object on second arc,
- Case 3: Driver on first arc and object beyond EVC,
- Case 4: Driver on first arc and object on second arc,
- Case 5: Driver on second arc and object beyond EVC, and
- Case 6: Driver and object on second arc.

These cases are indicated by the numbers in circles in Figure 6. The height of obstacle above the first tangent in given by

$$y_3 = c + r_2(L - d)^2/2 + (d - L_1)A \qquad L \geq d \geq L_1 \tag{18a}$$

$$y_3 = c + (d - L_1)A \qquad d \geq L \tag{18b}$$

where

y_3 = height of obstacle above the first tangent,
c = height of obstacle above the sag curve, and
d = distance between obstacle and BVC.

The following relationship is also true for all cases:

$$y_3 = (y_1S_2 + y_2S_1)/(S_1 + S_2) \tag{19}$$

where

y_1 = height of driver eye above the first tangent,
y_2 = height of top of object above the first tangent,
S_1 = distance between the obstacle and driver, and
S_2 = distance between the obstacle and object.

The sight distance component, S_1 and S_2, are given by

$$S_1 = d - T \tag{20}$$

$$S_2 = w - z \tag{21}$$

where

T = distance between the driver and BVC [T is negative if the driver is before BVC (on tangent) and positive if the driver is beyond BVC (on curve)], and
z = distance between the obstacle and PVI.

The available sight distance, S, which is the sum of S_1 and S_2, is given by

$$S = L_1 + w - T \tag{22}$$

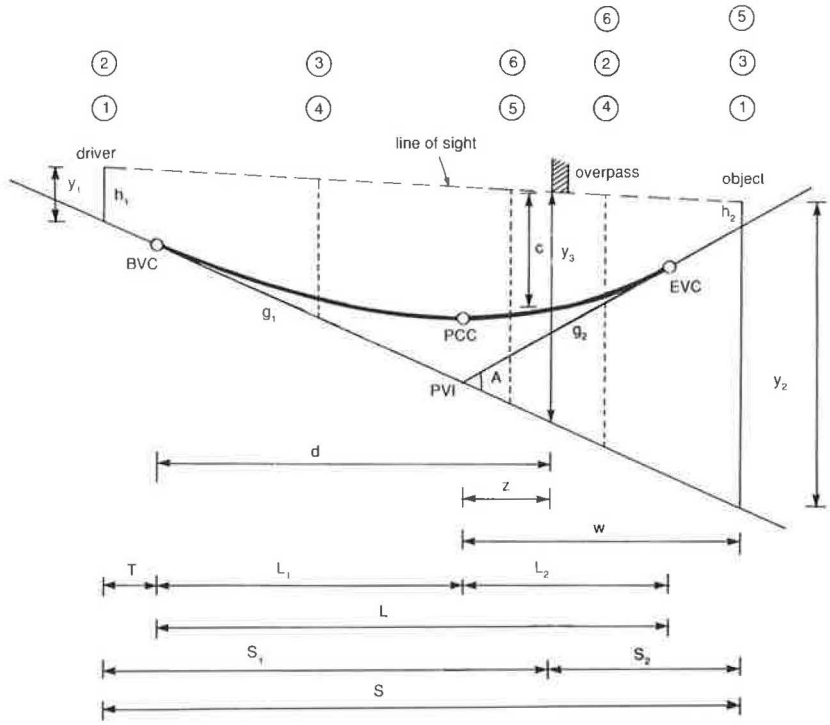

FIGURE 6 Geometry of sight distance for overhead control on an unsymmetrical sag curve (numbers in circles indicate various cases).

The variables y_1 and y_2 of Equation 19 are derived next for various cases and used along with Equations 18 and 19 to develop a relationship for w.

Case 1: Driver Before BVC and Object Beyond EVC

In this case, y_1 and y_2 are given by

$$y_1 = h_1 \tag{23}$$

$$y_2 = h_2 + wA \tag{24}$$

where

h_1 = height of driver eye above the sag curve,
h_2 = height of object above the sag curve, and
w = distance between the object and PVI.

Substituting for S_2 and y_2 (Equations 21 and 24) into Equation 19 and solving for w,

$$w = [y_3(z - S_1) - y_1 z + h_2 S_1]/(y_3 - y_1 - AS_1) \tag{25}$$

in which y_1 is given by Equation 23.

Case 2: Driver Before BVC and Object on Second Arc

In this case, y_1 is given by Equation 23, and y_2 is given by

$$y_2 = h_2 + r_2[L_2 - w]^2/2 + wA \tag{26}$$

Substituting for S_2 and y_2 (Equations 21 and 26) into Equation 19 and solving for w,

$$w = [-b + (b^2 - 4ac)^{1/2}]/2a \tag{27}$$

where

$$a = r_2 S_1/2 \tag{28}$$

$$b = y_1 - y_3 + S_1[A - r_2 L_2] \tag{29}$$

$$c = z(y_3 - y_1) + S_1[h_2 + r_2 L_2^2/2 - y_3] \tag{30}$$

in which r_2 and y_1 are given by Equations 2 and 23.

Case 3: Driver on First Arc and Object Beyond EVC

In this case, y_2 is obtained using Equation 24, and y_1 is given by

$$y_1 = h_1 + r_1 T^2/2 \tag{31}$$

This case is similar to Case 1. The relationship for w is given by Equation 25, where y_1 in this equation is obtained using Equation 31.

Case 4: Driver on First Arc and Object on Second Arc

In this case, y_1 and y_2 are given by Equations 31 and 26. Similar to Case 2, the relationship for w is given by Equation 27, where y_1 is obtained using Equation 31.

Case 5: Driver on Second Arc and Object Beyond EVC

In this case, y_2 is given by Equation 24, and y_1 is given by

$$y_1 = h_1 + r_2(L - T)^2/2 + A(T - L_1) \quad (32)$$

Similar to Case 1, the relationship for w is given by Equation 25, where y_1 is obtained using Equation 32.

Case 6: Driver and Object on Second Arc

In this case, y_1 and y_2 are given in Equations 32 and 26. Similar to Case 2, the relationship for w is given by Equation 27, where y_1 is obtained using Equation 32.

As previously indicated, the obstacle was assumed to lie on the second arc or beyond EVC. If the obstacle lies on the first arc or before BVC, y_3 of Equations 18a and 18b becomes

$$y_3 = c + r_1 d^2/2 \qquad 0 \le d \le L_1 \quad (33a)$$

$$y_3 = c \qquad d < 0 \quad (33b)$$

The relationships of Cases 1–4 are then applied using y_3 of Equations 33a and 33b. Cases 5 and 6 are not applicable in this situation, but two more cases need to be considered (when w of Equation 27 is negative). Case A has the driver before BVC and the object on the first arc, and Case B has the driver beyond BVC and the object on the first arc. The relationships for Cases A and B are the same as those for Cases 2 and 4, respectively, except that in Equations 28–30, r_2 and L_2 are replaced by r_1 and L_1, and A is set equal to zero. After w has been computed (Equation 27), S is computed using Equation 22, with w being negative.

Procedure for Calculating S_m

The minimum sight distance is determined using an iterative procedure. The available sight distance S is computed for consecutive values of T until the minimum value is reached. The computation steps are as follows:

1. Compute y_1 for Cases 1, 3, and 5 (Equations 23, 31, and 32).
2. Compute w for these three cases (Equation 25):
   a. If $w > L_2$, the object is beyond EVC. This corresponds to Case 1, 3, or 5 depending on whether the driver is before BVC, on first arc, or on second arc, respectively.
   b. If $w \le L_2$, the object is on the second arc. This corresponds to Case 2, 4, or 6 depending on the driver's location. Compute the corresponding w (Equation 27).
   c. If $w < 0$, reverse the variables and set $A = 0$. Use Case 2 or 4, depending on the driver's location. Compute w (Equation 27).
3. Compute the available sight distance (Equation 22).

A computer program implementing this procedure was prepared, and its logical flow is shown in Figure 7. The geometric characteristics of the curve L, L_1 (or L_2), and A and the location and height of the obstacle, d and c, must be known or measured. The available sight distance, S, is computed for an initial negative value of T. The procedure is repeated for successively smaller values of T (using an increment ΔT) until $S < S'$, where S' is the available sight distance of the previous iteration. At this point, the minimum sight distance has just been reached and $S_m = S'$. The computer program can also be used to determine the required sag curve length that satisfies a desirable sight distance, given d, c, and other curve characteristics.

Sight Distance Characteristics

The sight distance for overhead control on unsymmetrical sag curves exhibits interesting characteristics. These are discussed in relation to a comparison with symmetrical curves and effect of obstacle location.

Comparison with Symmetrical Curves

As indicated, the relationships between the curve length and sight distance for symmetrical sag curves have been developed for situations in which the obstacle is located at PVI (*4*). These situations can be obtained by setting $L_2 = L/2$ in the developed relationships. Figure 8 shows the variations of the available sight distance along an unsymmetrical curve with an obstacle located at PVI. The variations of sight distance for a symmetrical curve ($R = 0.5$) with the same length are also shown.

The sight distance profile and minimum sight distance on the unsymmetrical curve vary with the direction of travel as shown in Figure 8. In this case, where the overpass lies at PVI, the minimum sight distance is smaller when the driver travels from the flatter to the sharper arc. For the symmetrical curve, the sight distance profile is the same in both directions of travel with $S_m = 1{,}450$ ft. For $R = 0.3$, $S_m = 1{,}167$ ft, which differs from that of the symmetrical curve by about −20 percent. This means that a larger length of the unsymmetrical curve is needed to satisfy a specific sight distance, under similar geometric and operating conditions.

Effect of Obstacle Location

The variations of minimum sight distance as the obstacle location changes are shown in Figure 9 for both travel directions on an unsymmetrical curve. As noted, if the overpass lies at PVI or on the first (flatter) arc, the critical travel direction is from the first to the second arc. If the overpass lies on the second arc, both travel directions may be critical depending on the overpass location. In Figure 9, the travel direction from the second to the first arc becomes critical when the overpass is on the second arc at about 300 ft or more from PVI. The circles in the figure are the points at which the driver or object is at the beginning or end of the curve, where a change in curvature in the sight distance profile occurs.

For the symmetrical curve, the minimum sight distance does not depend on the location of obstacle when both the driver

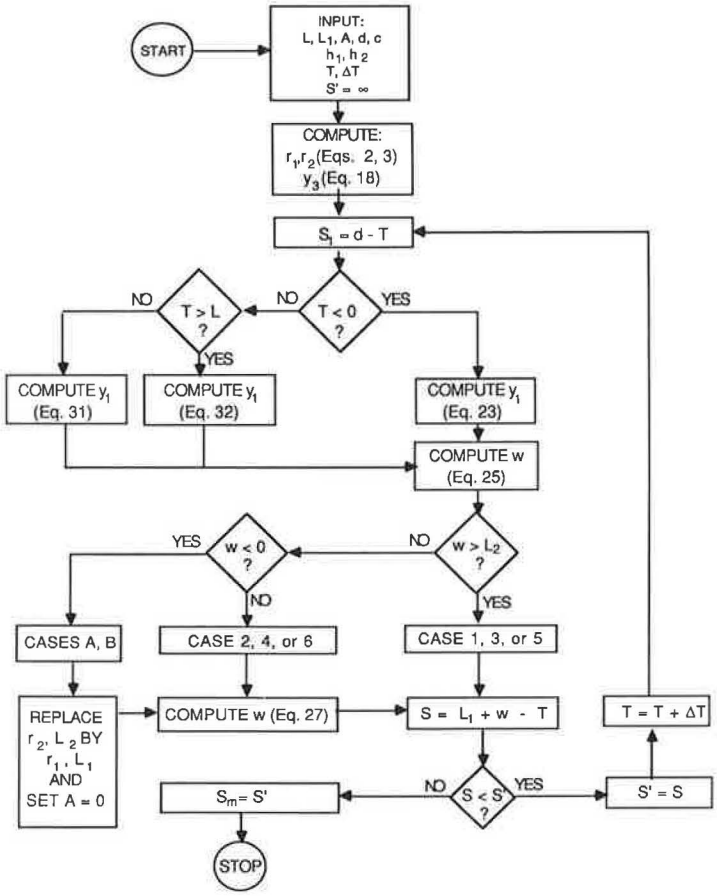

FIGURE 7 Calculating minimum sight distance for overhead control on unsymmetrical sag curves–logical flow.

and object are on the curve. For the unsymmetrical curve, the minimum sight distance occurs when the obstacle is somewhere on the sharper arc. The minimum sight distance exceeds that of the symmetrical curve when the obstacle is located on the flatter arc at a distance greater than about 200 ft from PVI.

Evaluation and Design Values

For overhead control, Table 1 shows the minimum sight distance for sag curve lengths ranging from 200 ft to 1,200 ft, for $R = 0.4$ and 0.5. The following five locations of the obstacle are considered:

1. $d = 0$ (obstacle at BVC),
2. $d = L_1/2$ (obstacle at the midpoint of first arc),
3. $d = L_1$ (obstacle at PVI),
4. $d = L_1 + L_2/2$ (obstacle at the midpoint of second arc), and
5. $d = L$ (obstacle at EVC).

Table 1, which is applicable to highways with trucks, is based on a truck driver eye height of 9 ft and an object height of 1.5 ft. This eye height is conservative because typically truck driver eye height ranges from 71.5 to 112.5 in. (*9,17–19*). The object height of 1.5 ft was suggested in the 1965 AASHO policy (*2*). This height may represent the taillight or a discernible portion of an oncoming vehicle. Table 1 is based on a vertical clearance of 14.5 ft, which is the minimum value suggested by AASHTO (*4*).

A comparison of the minimum sight distance for $A = 12$ percent is shown in Figure 10 for $R = 0.4$ and 0.5 for three locations of the obstacle. There is almost no difference in S_m between symmetrical and unsymmetrical curves when the overpass lies at PVI. However, the sight distance of the unsymmetrical curve increases when the overpass lies at BVC (near the flatter arc) and decreases when the overpass lies at EVC (near the sharper arc). For example, for $L = 1{,}200$ ft, the increase in S_m when the overpass lies at BVC is 25 percent and the decrease when it lies at EVC is 18 percent.

SUMMARY AND CONCLUSIONS

The AASHTO Green Book points out the need for using unsymmetrical vertical curves to accommodate clearance and other controls (*4*). For these curves, however, no relationships are available to relate the available sight distance to the curve parameters and other operating characteristics. Sight distance relationships for unsymmetrical sag curves are derived for both headlight and overhead obstacle controls. Simple design

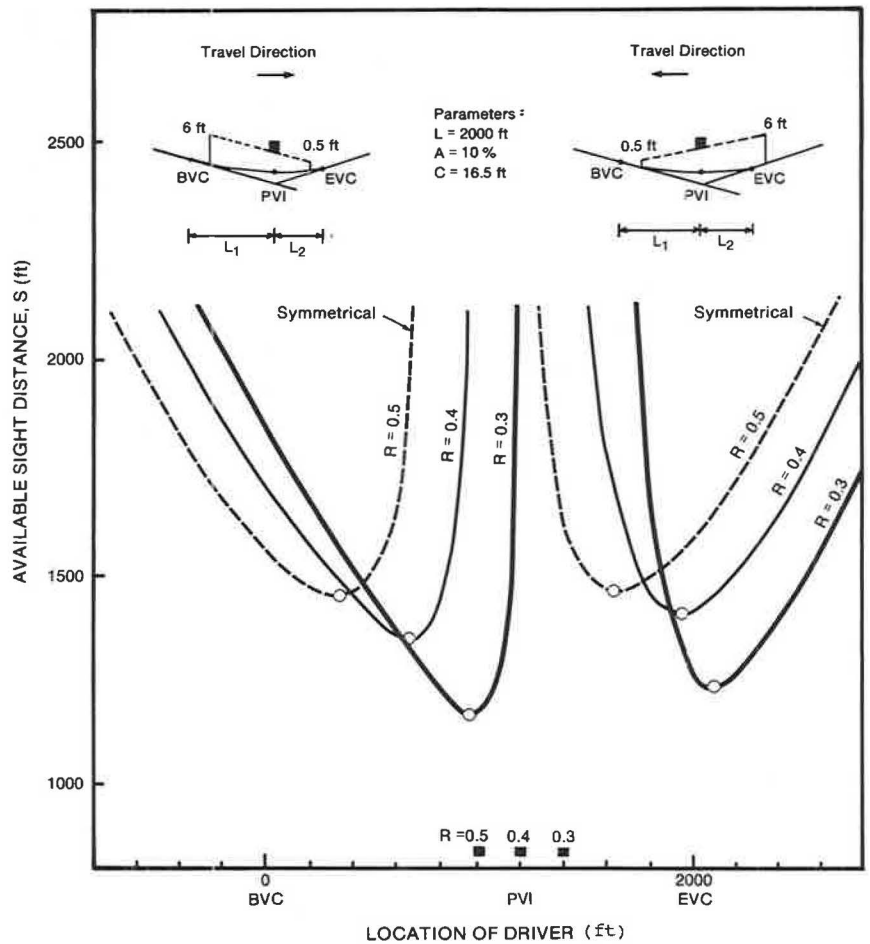

FIGURE 8 Sight distance profiles of symmetrical and unsymmetrical sag curves for overhead control (obstacle at PVI).

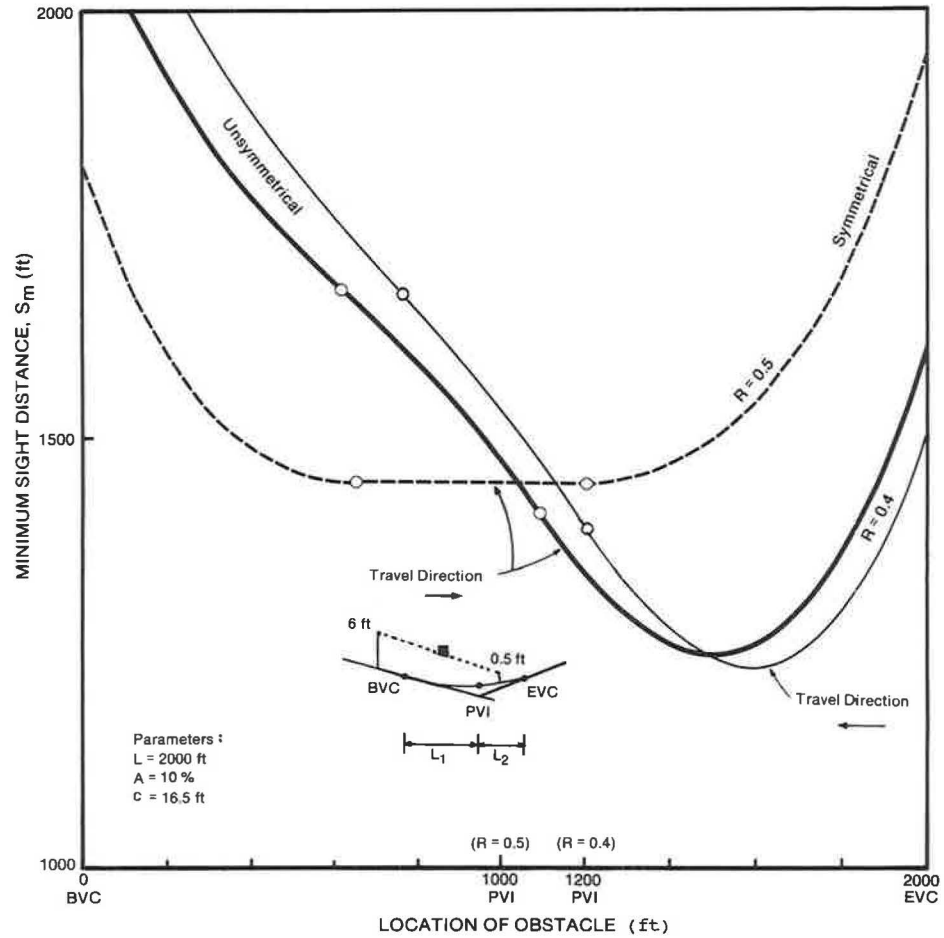

FIGURE 9 Variations of minimum sight distance with obstacle location.

TABLE 1 MINIMUM SIGHT DISTANCE FOR OVERHEAD CONTROL ON UNSYMMETRICAL SAG CURVES FOR HIGHWAYS WITH TRUCKS[a]

Algeb. Diff. Grade (%)	Overp. Loc.[c]	Length of sag curve (ft)											
		200		400		600		800		1000		1200	
		R=.4[b]	R=.5	R=.4	R=.5	R=.4	R=.5	R=.4	R=.5	R=.4	R=.5	R=.4	R=.5
6	1	780	750	960	900	1130	1050	1300	1190	1460	1320	1620	1450
6	2	720	700	840	810	950	910	1070	1020	1190	1120	1300	1220
6	3	700	700	800	800	900	900	1010	1010	1100	1110	1200	1200
6	4	680	700	770	810	860	910	950	1020	1030	1120	1100	1220
6	5	720	750	840	900	960	1050	1070	1190	1180	1320	1260	1450
8	1	630	600	810	750	970	890	1140	1030	1290	1150	1440	1260
8	2	570	550	690	660	800	760	920	870	1040	960	1150	1040
8	3	550	550	650	650	760	750	850	860	940	950	1030	1040
8	4	540	550	630	660	710	760	790	870	860	960	920	1040
8	5	570	600	690	750	810	890	910	1030	990	1150	1070	1260
10	1	540	510	710	660	880	800	1040	920	1180	1030	1320	1120
10	2	480	470	600	570	710	670	830	770	940	850	1050	930
10	3	460	460	560	560	660	670	750	760	840	850	920	930
10	4	450	470	540	570	620	670	690	770	750	850	800	930
10	5	480	510	600	660	710	800	790	920	870	1030	940	1120
12	1	480	450	650	600	810	730	960	840	1100	940	1220	1030
12	2	420	410	540	510	650	610	770	700	870	780	970	850
12	3	400	400	500	500	600	600	690	690	770	770	850	850
12	4	390	410	480	510	550	610	610	700	670	780	720	850
12	5	420	450	540	600	630	730	710	840	780	940	850	1030
14	1	440	410	600	550	760	670	900	780	1030	870	1150	950
14	2	380	360	490	470	610	560	720	640	820	720	910	780
14	3	360	360	460	460	550	560	640	640	720	720	790	780
14	4	350	360	430	470	500	560	560	640	610	720	660	780
14	5	380	410	490	550	580	670	650	780	720	870	780	950
16	1	410	380	570	520	720	630	860	730	980	810	1080	890
16	2	350	330	460	430	580	520	680	600	770	670	860	730
16	3	330	330	430	430	520	520	600	600	670	670	740	730
16	4	310	330	400	430	460	520	510	600	560	670	610	730
16	5	350	380	450	520	540	630	610	730	670	810	730	890

[a] Driver eye height = 9.0 ft
Object height = 1.5 ft

[b] Ratio of shorter arc to total curve length

[c]
1: Overpass at BVC
2: Overpass at midpoint of first arc
3: Overpass at PVI
4: Overpass at midpoint of second arc
5: Overpass at EVC

Note: minimum sight distances are expressed in feet. Vertical clearance = 14.5 ft.

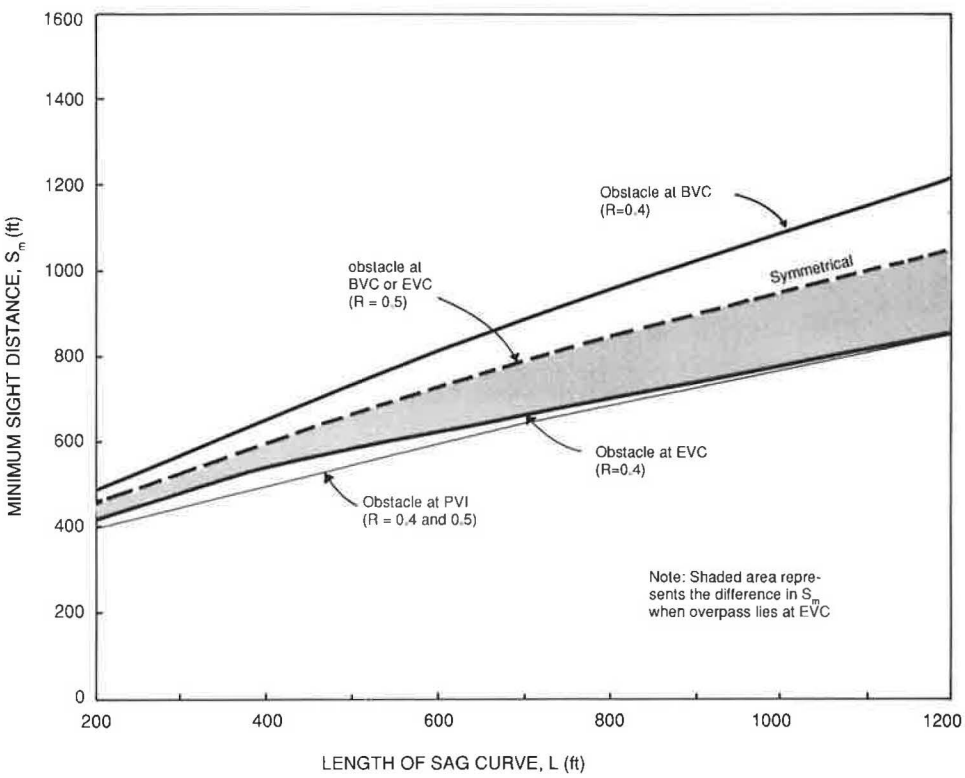

FIGURE 10 Comparison of the minimum sight distance for different obstacle locations for A = 12 percent (highways with trucks).

graphs and tables of the curve length requirements and minimum sight distance are established.

The results show that unsymmetrical sag curves must be much longer than symmetrical curves, under similar conditions. The sight distance profiles of unsymmetrical curves with overhead control exhibit certain characteristics that may have important design implications. This strongly supports the early use of the developed models in the design and evaluation of unsymmetrical sag curves. The models should be useful in maintaining or achieving adequate sight distances on unsymmetrical sag curves, and thus making highways safer.

ACKNOWLEDGMENT

This work was supported by the Natural Sciences and Engineering Research Council of Canada.

REFERENCES

1. *A Policy on Sight Distance for Highway, Policies on Geometric Highway Design*. AASHO, Washington, D.C., 1940.
2. *A Policy on Geometric Design of Rural Highways*, AASHO, Washington, D.C., 1965.
3. *A Policy on Design Standards for Stopping Sight Distance*. AASHO, Washington, D.C., 1971.
4. *A Policy on Geometric Design of Highways and Streets*. AASHTO, Washington, D.C., 1984.
5. T. F. Hickerson. *Route Location and Design*. McGraw-Hill Book Company, New York, 1964.
6. H. C. Ives and P. Kissam. *Highway Curves*. John Wiley & Sons, London, England, 1956.
7. P. F. Olson, D. E. Cleveland, P. S. Fancher, L. P. Kostyniuk, and L. W. Schneider. *NCHRP Report 270: Parameters Affecting Stopping Sight Distance*. TRB, National Research Council, Washington, D.C., 1984.
8. T. R. Neuman. New Approach to Design for Stopping Sight Distance. In *Transportation Research Record 1208*, TRB, National Research Council, Washington, D.C., 1989.
9. D. W. Harwood and J. C. Glennon. Passing Sight Distance Design for Passenger Cars and Trucks. In *Transportation Research Record 1208*, TRB, National Research Council, Washington, D.C., 1989.
10. J. C. Glennon. New and Improved Model of Passing Sight Distance on Two-Lane Highways. In *Transportation Research Record 1195*, TRB, National Research Council, Washington, D.C., 1988, pp. 132–137.
11. H. W. McGee. Reevaluation of the Usefulness and Application of Decision Sight Distance. In *Transportation Research Record 1208*, TRB, National Research Council, Washington, D.C., 1989, pp. 85–89.
12. T. R. Neuman, J. C. Glennon, and J. E. Leish. *Stopping Sight Distance—An Operational and Cost Effectiveness Analysis*. Report FHWA/RD-83/067. FHWA, U.S. Department of Transportation, Washington, D.C., 1982.
13. T. R. Neuman and J. C. Glennon. Cost-Effectiveness of Improvements to Stopping Sight Distance. In *Transportation Research Record 923*, TRB, National Research Council, Washington, D.C., 1984, pp. 26–34.
14. J. C. Glennon. Effects of Sight Distance on Highway Safety. In *State-of-the-Art Report 6*. TRB, National Research Council, Washington, D.C., 1987.
15. C. F. Meyer. *Route Surveying and Design*. International Textbook Company, Scranton, Pa., 1971.
16. C. J. Khisty. *Transportation Engineering: An Introduction*. Prentice Hall, Englewood Cliffs, New Jersey, 1990.
17. P. B. Middleton, M. Y. Wong, J. Taylor, H. Thompson, and J. Bennett. *Analysis of Truck Safety on Crest Vertical Curves*. Report FHWA/RD-86/060. FHWA, U.S. Department of Transportation, Washington, D.C., 1983.
18. J. W. Burger and M. U. Mulholland. *Plane and Convex Mirror Sizes for Small to Large Trucks*. NHTSA, U.S. Department of Transportation, Washington, D.C., 1982.
19. Urban Behavioral Research Associates. *The Investigation of Driver Eye Height and Field of Vision*. FHWA, U.S. Department of Transportation, Washington, D.C., 1978.

Publication of this paper sponsored by Committee on Geometric Design.