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 control 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 \((I-4)\). 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 AASHTO 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,
FIGURE 1 Geometry of sight distance for headlight control on an unsymmetrical sag curve.
Then, Hickerson's formulas for the rates of change in grade can be written in terms of $R$ as follows:

\[ r_1 = \frac{(A/L)R_1(1 - R)}{1 - R} \]
\[ r_2 = \frac{(A/L)(1 - R)/R}{L} \]

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 $AIL$. 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 second arc will be sharper and the first arc will be flatter than a symmetrical curve with the same length. Note that the variables $g_1, g_2, A$ 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 $\alpha$ 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

\[ y = h_1 + S_m \tan \alpha \]

**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

\[ y = (S_m - L_2)A \]

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

\[ L = (S_m/R) - (h_1 + S_m \tan \alpha)/RA \quad S_m \geq L \]

**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

\[ y = (S_m - L_2)A + r_1(L - S_m)/2 \]

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

\[ aL^2 + bL + c = 0 \]

where

\[ a = (1 - 2R)RA \]
\[ b = 2(1 - R)(h_1 + S_m \tan \alpha) - 2(1 - 2R)S_mA \]
\[ c = -ARS_m^2 \]

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

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

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

The variable $y$ in Figure 1c is written as

\[ y = r_2S_m^2/2 \]

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

\[ L = \left[(1 - R)/R\right]AS_m^2/2(h_1 + S_m \tan \alpha) \quad S_m = L_2 \]

Comparison with Symmetrical Curves

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

\[ L_s = 2S_m - 2(h_1 + S_m \tan \alpha)/A \quad S_m \geq L_s \]

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

\[ L_r = AS_m^2/2(h_1 + S_m \tan \alpha) \quad S_m \leq L_r \]
Equations 15 and 16 are the known formulas for symmetrical curves for \( S_m \geq L_2 \) and \( S_m \leq L_1 \), 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

\[
\frac{1}{2R} \leq \frac{L/L_1}{(1 - R)/R} \quad (17)
\]

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 [sec, 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 5000.3 = 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 \( (g_1 + r_1 L_1 > 0) \). The second arc controls if the grade of the tangent at PCC is negative \( (g_1 + r_1 L_1 < 0) \).

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 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 ($R = 0.4$).
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

\[
y_3 = c + r_2 (L - d)^2/2 + (d - L_1)A \quad L_1 \geq d \geq L_1
\]

\[
y_3 = c + (d - L) A \quad d \geq L
\]

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:

\[
y_3 = (y_3S_2 + y_2S_1)/(S_1 + S_2)
\]

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

\[
S_1 = d - T
\]

\[
S_2 = w - z
\]

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

\[
S = L_1 + w - T
\]
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

\[ y_1 = h_1 \]  
\[ y_2 = h_2 + wA \]  

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 $w$,

\[ w = \left[ -b + \sqrt{b^2 - 4ac} \right] / 2a \]  

where

\[ a = r_2 S_1 / 2 \]  
\[ b = y_1 - y_2^* + S_1 [A - r_2 L_2] \]  
\[ c = z^*(y_2 - y_1) + S_1 [h_2 + r_2 L_2^*/2 - y_3] \]

in which $r_2$ and $y_1$ are given by Equations 2 and 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

\[ y_2 = h_2 + r_2 [L_2 - w^2 / 2 + wA] \]  

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

\[ w = \left[ -b + \sqrt{b^2 - 4ac} \right] / 2a \]  

where

\[ a = r_2 S_1 / 2 \]  
\[ b = y_1 - y_2^* + S_1 [A - r_2 L_2] \]  
\[ c = z^*(y_2 - y_1) + S_1 [h_2 + r_2 L_2^*/2 - y_3] \]

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

\[ y_1 = h_1 + r_1 T^2 / 2 \]  

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.
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 $w \leq L_2$, 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 $\Delta T$) 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.

**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

$$y_1 = h_1 + r_1(L - T)^2/2 + A(T - L_1) \quad (32)$$

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

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

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

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, $r_1$ and $L_1$ are replaced by $r_2$ and $L_2$, 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 $w \leq L_2$, 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).

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.

**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**

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
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>
<thead>
<tr>
<th>Algeb. Overp.</th>
<th>Length of sag curve (ft)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grade (%)</td>
<td>200</td>
</tr>
<tr>
<td>---------------</td>
<td>------</td>
</tr>
<tr>
<td></td>
<td>R=.4</td>
</tr>
<tr>
<td>6 1</td>
<td>780</td>
</tr>
<tr>
<td>6 2</td>
<td>720</td>
</tr>
<tr>
<td>6 3</td>
<td>700</td>
</tr>
<tr>
<td>6 4</td>
<td>680</td>
</tr>
<tr>
<td>6 5</td>
<td>720</td>
</tr>
<tr>
<td>8 1</td>
<td>630</td>
</tr>
<tr>
<td>8 2</td>
<td>570</td>
</tr>
<tr>
<td>8 3</td>
<td>550</td>
</tr>
<tr>
<td>8 4</td>
<td>540</td>
</tr>
<tr>
<td>8 5</td>
<td>570</td>
</tr>
<tr>
<td>10 1</td>
<td>540</td>
</tr>
<tr>
<td>10 2</td>
<td>480</td>
</tr>
<tr>
<td>10 3</td>
<td>460</td>
</tr>
<tr>
<td>10 4</td>
<td>430</td>
</tr>
<tr>
<td>10 5</td>
<td>480</td>
</tr>
<tr>
<td>12 1</td>
<td>480</td>
</tr>
<tr>
<td>12 2</td>
<td>420</td>
</tr>
<tr>
<td>12 3</td>
<td>400</td>
</tr>
<tr>
<td>12 4</td>
<td>390</td>
</tr>
<tr>
<td>12 5</td>
<td>420</td>
</tr>
<tr>
<td>14 1</td>
<td>440</td>
</tr>
<tr>
<td>14 2</td>
<td>380</td>
</tr>
<tr>
<td>14 3</td>
<td>360</td>
</tr>
<tr>
<td>14 4</td>
<td>350</td>
</tr>
<tr>
<td>14 5</td>
<td>380</td>
</tr>
<tr>
<td>16 1</td>
<td>410</td>
</tr>
<tr>
<td>16 2</td>
<td>350</td>
</tr>
<tr>
<td>16 3</td>
<td>330</td>
</tr>
<tr>
<td>16 4</td>
<td>310</td>
</tr>
<tr>
<td>16 5</td>
<td>350</td>
</tr>
</tbody>
</table>

Table 1: Minimum Sight Distance for Overhead Control on Unsymmetrical Sag Curves for Highways with Trucks

- Driver eye height = 9.0 ft
- Object height = 1.5 ft
- Overpass at BVC
- Overpass at midpoint of first arc
- Overpass at PVI
- Overpass at midpoint of second arc
- Overpass at EVC

Note: All 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