Appendix K

Example Calculations

Appendix K includes example calculations for the Road Design Manual. The examples are numbered to correspond with the associated chapter material, as described below.

- Sight Distance (Chapter 2)
- Horizontal Alignment (Chapter 3)
- Vertical Alignment (Chapter 4)
- Roadside Safety (Chapter 9)
- Quantity Summaries (Chapter 13)

Sight Distance Example Calculations

Example 2-1: Horizontal Sight Distance – Middle Ordinate

Given: Design Speed = 60 mph
R = 1,400 feet

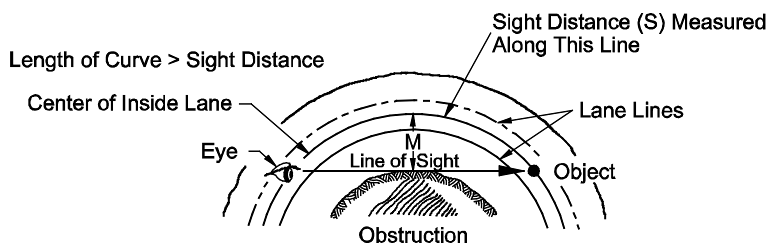
Problem: Determine the horizontal clearance requirements for the horizontal curve using the desirable stopping sight distance (*SSD*) value.

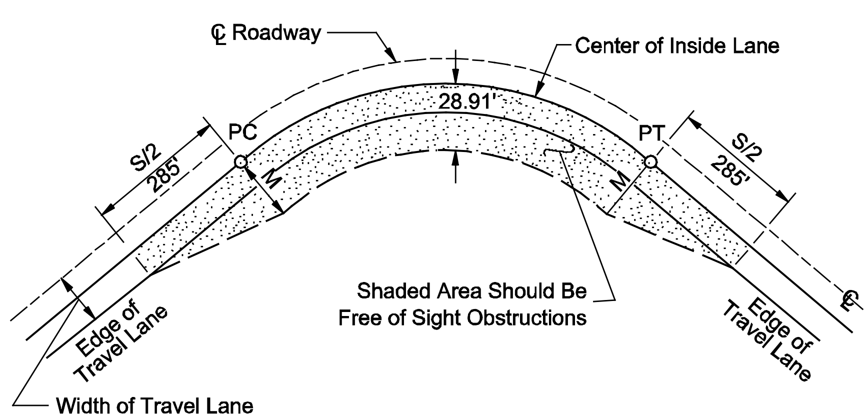
Solution: Chapter 2, Exhibit 2-1 yields a *SSD* = 570′. Using Appendix F, Equation F.2-1 for horizontal clearance:

$$M = R\left(1 - \cos\left(\frac{90° \cdot S}{\pi \cdot R}\right)\right)$$

$$M = 1400\left(1 - \cos\left(\frac{(90°)(570)}{(\pi)(1400)}\right)\right) = 28.91'$$

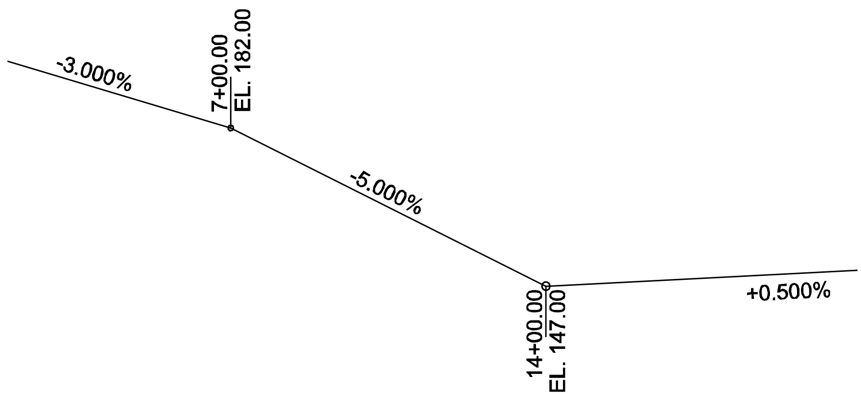
The exhibit below illustrates the horizontal clearance requirements for the entering and exiting portion of the horizontal curve.





Example 2-2: Stopping Sight Distance with Vertical Curves

Given: The grade line for a 60-mph design speed, two-lane, two-way rural roadway is shown below. Give consideration to the effect of grades on *SSD*.



Problem: Determine the appropriate profile that meets minimum stopping sight distance, as well as consider passing sight distance for additional refinement.

Solution:

1. Since the grades are 3 percent and greater, determine stopping sight distance adjusted for downgrades. The 5-percent grade is the maximum of the downgrades, and will be used for calculating *SSD*. Using Chapter 2, Equation 2.8-3:

$$SSD_{\text{Downgrades}} = 1.47Vt + \frac{V^2}{30\left[\left(\frac{a}{32.2}\right) - G\right]}$$

where:

SSD = stopping sight distance, feet.

V = design speed, mph

t = brake reaction time, 2.5 seconds

a = deceleration rate, 11.2 foot per second squared

G = gradient, feet/feet

$$SSD_{-5\%} = 1.47 \times 60 \times 2.5 + \frac{60^2}{30[(11.2 \div 32.2) - .05]} = 623.4\text{, Round} \Rightarrow \underline{624'}$$

2. Second, calculate the minimum length for the crest curve for the calculated *SSD* using Equation 4.4-1:

$$L = \frac{AS^2}{200(\sqrt{h_1} + \sqrt{h_2})^2}$$

Where:

L = length of vertical curve, feet

A = algebraic difference between the two tangent grades, percent

S = sight distance, feet

h_1 = height of eye above road surface, feet

h_2 = height of object above road surface, feet

$$L = \frac{AS^2}{200 \times \left(\sqrt{h_1} + \sqrt{h_2}\right)^2} = \frac{2 \times 624^2}{2158} = 360.87'$$

3. Since this length is less than the *SSD*, Equation 4.4-2 can be used :

$$L = 2S - \frac{200\left(\sqrt{h_1} + \sqrt{h_2}\right)^2}{A}$$

Where:

L = length of vertical curve, feet

A = algebraic difference between the two tangent grades, percent

S = sight distance, feet

h_1 = height of eye above road surface, feet

h_2= height of object above road surface, feet

$$L = 2S - \frac{200 \times \left(\sqrt{h_1} + \sqrt{h_2}\right)^2}{A} = 2 \times 624 - (2158 \div 2) = 169'$$

The minimum curve length providing *SSD* is 169 feet, however the minimum curve length based on $L_{min} = 3V$ would be 180 feet.

4. Prior to finalizing the crest curve length, we'll determine the needed length for the sag curve based on *SSD*:

   Calculate the minimum length for the sag curve using Equation 4.4-7:

$$L = \frac{AS^2}{200h_3 + 3.5S}$$

Where:

L = length of vertical curve, feet

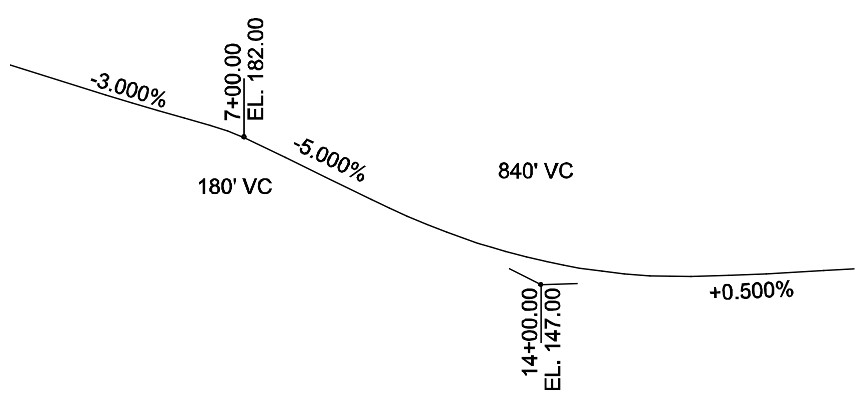
A = algebraic difference between the two tangent grades, percent

S = sight distance, feet

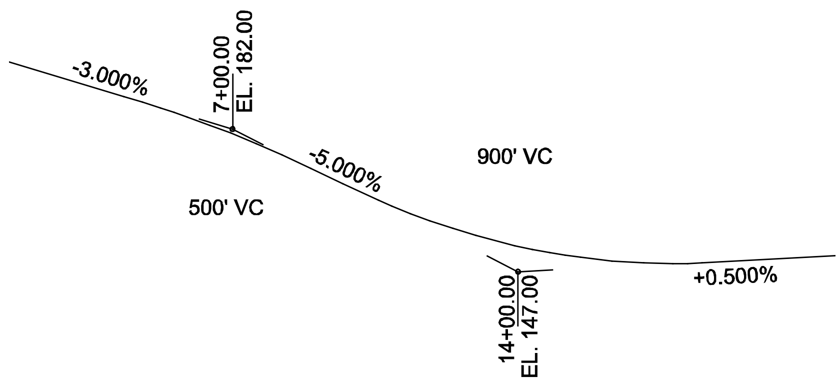
h_3 = height of headlights above pavement surface, feet

$$L = \frac{AS^2}{200 \times h_3 + 3.5S} = \frac{5.5 \times 624^2}{200 \times 2 + (3.5 \times 624)} = 828.78'$$

For this example, both curves can be designed to provide *SSD* adjusted for the 5 percent downgrade, using a 180-foot long crest and 840-foot sag curves (lengths rounded up for design), without curve overlap.



Additional Discussion: Rather than using the minimum lengths of curve calculated, consideration should be given to increasing the curve lengths to provide additional sight distance and reducing the length of the 5 percent grade. Using the curve lengths shown below, the 5 percent grade occurs at station 9+50 only, and reduces from that point in each direction.



Using equation 4.4-2 with the 500-foot crest length and solving for *S*, stopping sight and passing sight distances provided are 789.5 feet and 950 feet, respectively. Since both are influenced by the adjacent sag curve, graphical analysis shows that actual minimum sight distances provided are 825 feet *SSD* and 1080 feet *PSD*, meeting the criteria for 60 mph.

Since the sag curve is longer than the stopping sight distance provided, the minimum *SSD* provided can be found using equation 4.4-7, and is 670 feet whenever the vehicle and 1 degree rise in headlight are on the sag.

It is worth noting that the downgrade of the roadway during the braking operation is much lower than the 5 percent used to calculate required stopping sight distance for the sag curve. It varies from -3.65 to -.9 percent at the steepest point that *SSD* is at its minimum for the curve shown above. In this respect, using the *SSD* adjusted for grades is significantly more conservative when applied to sag curves compared to crest curves, and may warrant closer analysis for situations where site constraints or impacts limit curve length.

Example 2-3: Combination of Vertical and Horizontal Curves

Given: **Horizontal curve data**

PI = 50+00.00
Δ = 27°15′18″ (RT)
R = 3,000 feet
S = 4.0%
Design speed = 60 mph
Two-lane, two-way roadway with 12-foot travel lanes, 4-foot shoulders
Guardrail on the inside shoulder with face of rail at edge of shoulder
Guardrail post height = 30 inches

Symmetrical vertical curve data

G1 = +2.00%
G2 = -2.50%
VPI elev. = 1,308.00'
VPI station = 49+00.00
L = 2,000'

Problem: Graphically determine if the combination of horizontal and vertical curves provides Stopping Sight Distance (*SSD*) using CAD software.

Solution:

1. Draw the horizontal curve showing travel lanes, center of travel lanes, shoulders and guardrail.

2. Determine *SSD* for 60 mph from table in Exhibit 2-1. (*SSD* = 570')

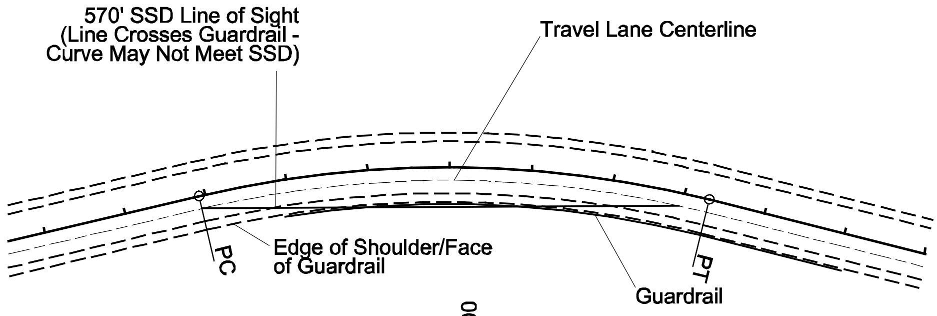
3. Draw a sight line the length of the *SSD* as a chord across the curve from the center of near travel lane to the center of near travel lane. If the line crosses the guardrail the curve may not meet *SSD*.

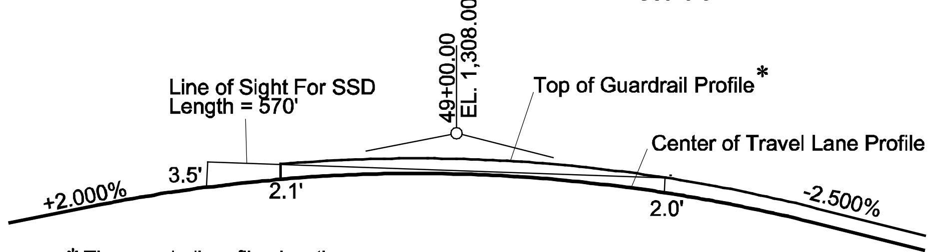
4. If the horizontal curve appears to provide a *SSD* line of sight, check the vertical profile for meeting *SSD* (step 5). If it appears that the curve does not meet the *SSD*, then graphically check the roadway profile with the guardrail profile shown to determine if the line of sight clears the top of the guardrail (step 6).

5. To graphically check the *SSD* of the roadway profile:
   a. Draw the profile for the area of the horizontal curve which in this case includes a crest vertical curve.
   b. Draw an element, to the same scale the profile was drawn, representing the *SSD*.
   c. Draw the element with a horizontal line of sight line the length of the *SSD* and with a vertical leg under each end, 3.5' high on the driver's eye height side and 2.0' high on the object height side.
   d. Place the element on the profile with the legs touching the profile.
   e. Move the element along the profile through the vertical curve while keeping the legs on the profile.
   f. If at any point the profile line crosses the line of sight part of the element, the curve does not meet *SSD*.

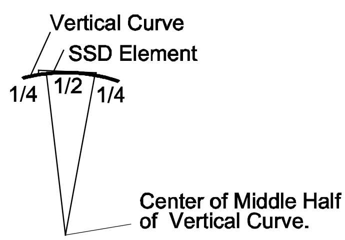
6. To graphically check the *SSD* on the roadway profile with the guardrail, draw the profile for the area of the horizontal curve which in this case includes a crest vertical curve. Draw the top of guardrail profile at the correct height above the roadway profile.
    a. The guardrail profile elevation = roadway profile elevation + (guardrail post height - (distance from the face of rail to the center of the travel lane x the roadway cross slope rate)).
    b. Draw an element, to the same scale the profile was drawn, representing the *SSD*.
    c. Draw the element with a horizontal line of sight line the length of the *SSD* and with a vertical leg under each end, 3.5' high on the driver's eye height side and 2.0' high on the object height side.
    d. Place the element on the roadway profile with the legs touching the profile.
    e. Move the element along the roadway profile through the vertical curve.
    f. If at any point the guardrail profile line crosses the horizontal part of the element, the vertical curve does not meet *SSD*.

This method can be used to check *SSD* and passing sight distance (*PSD*) on any combination of horizontal/vertical curves with possible sight restrictions caused by backslopes, rocks, fences, buildings, crops, etc. It can also be used to check *SSD* and *PSD* on multiple short vertical curves with little or no tangent grade between them.



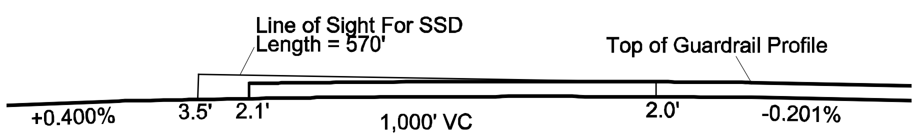


* The guardrail profile elevation =
travel lane centerline profile elevation + [guardrail post height (2.5') - distance from the face of rail to the center of the travel lane (10') x the cross slope rate (0.4)] =
travel lane centerline profile elevation + [2.5'- (10' x .04)]



To move the SSD element through the vertical curve, rotate the element about the center of middle half of the vertical curve. Some tweaking of the element may be required near the edges of the vertical curve.

The line of sight for the *SSD* is crossed by both the face of guardrail horizontal alignment and by the top of guardrail profile. Therefore, this combination of vertical curve, horizontal curve, and guardrail offset does not meet *SSD*. The design team may consider widening the shoulder, eliminating the roadside hazard that is requiring guardrail, using a larger radius horizontal curve, flattening the grades, and/or using a longer vertical curve. The exhibit shown below illustrates an example of modifications required of the profile to meet the *SSD*. It appears that increasing the horizontal curve radius or increasing the shoulder width/guardrail offset may be more practical ways to achieve the required *SSD* in this case.

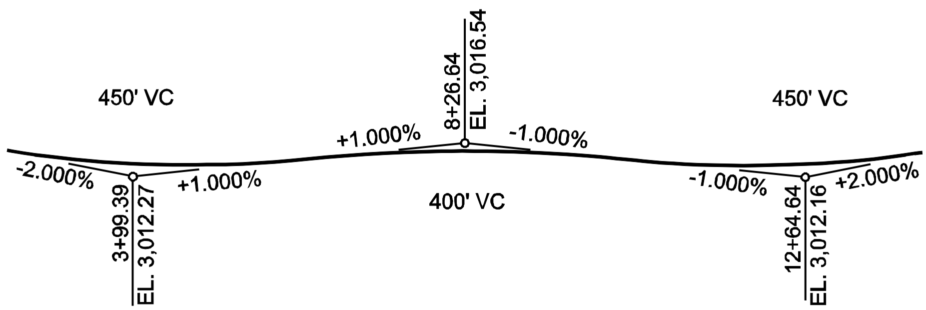


Example Drawings Not To Scale Or Proportional.

Example 2-4: Passing Sight Distance

Given: Refer to the below crest vertical curve for given information.

Problem: For a design speed of 60 mph on a rural, two-lane, two-way highway, does the following crest vertical curve meet minimum passing sight distance (*PSD*)? Give consideration to the multiple curves.



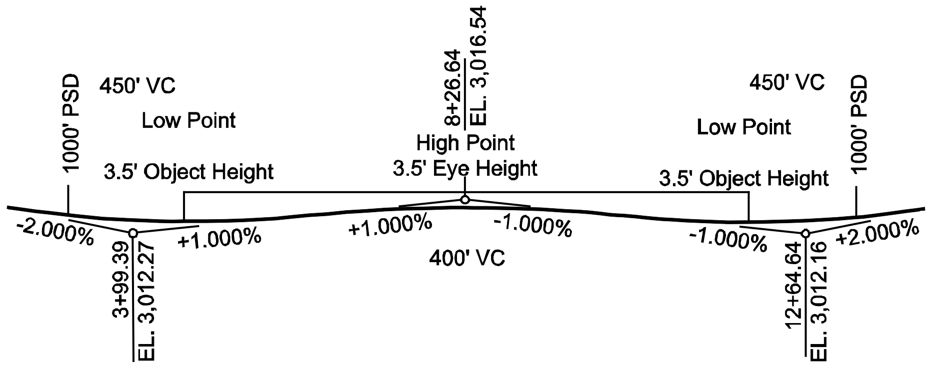
Solution:

1. From Exhibit 2-10, the minimum passing sight distance for a design speed of 60 mph for the above crest vertical curve is 1,000′. Using the passing sight distance of 1,000′ to calculate the length of vertical curve when *S* is greater than *L*, use Equation 4.4-2:

$$L = 2S - \frac{200 \times \left(\sqrt{h_1} + \sqrt{h_2}\right)^2}{A}$$

The length of vertical curve required would be 600′. From inspection, the crest vertical curve (Length = 400′) is less than the minimum required crest vertical curve (Length = 600′) when designing for passing sight distance. If this crest vertical curve was connected by lengthy tangents sections extending at +1.0% and -1.0%, instead of short tangent sections connecting to sag vertical curves as shown above, then this crest vertical curve would not meet the minimum passing sight distance for 60 mph design speed.

Consideration must be given for passing sight distance across multiple curves when they are connected by short tangents. If you plot the height of eye (3.5′) at the high point of the crest vertical curve and the height of object (3.5′) at the low point of both sag vertical curves, you can graphically determine if this crest vertical curve meets minimum passing sight distance.



Refer to the above diagram for plotting sight distance across the crest vertical curve. Plotting the low points of both sag vertical curves (at 3.5 foot object height) and the high point of the crest vertical curve (at 3.5 foot eye height), you can visually see that the sight distance is sufficient. If passing sight distance is sufficient at the low points, then it will also be sufficient at 1,000 feet.

In conclusion, the crest vertical curve does meet the minimum requirements for 1,000 feet passing sight distance. If consideration was not given to passing sight distance across multiple curves, then this crest vertical curve would not have met the minimum passing sight distance.

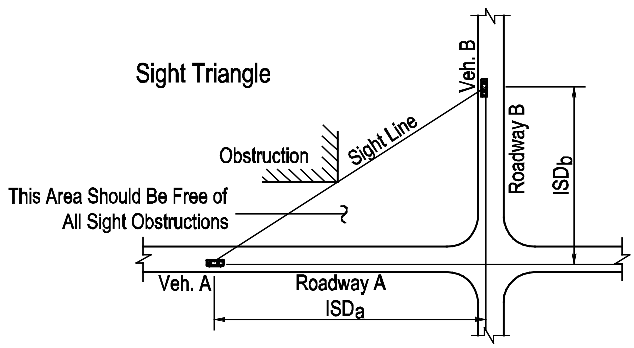
Example 2-5: Intersection Sight Distance (*ISD*) – No Traffic Control

Given: No traffic control intersection.

Design speed: 35 mph (Roadway A)

Design speed: 25 mph (Roadway B)

Note: This exhibit is not applicable for State highways.



Design Speed (mph)	15	20	25	30	35	40	45	50
***Intersection Sight Distance (ft)**	70	90	115	140	165	195	220	245

Note: For approach grades greater than 3%, multiply the sight distance values in this table by the appropriate adjustment factor from Appendix F, Exhibit F-8. The grade adjustment is based on the approach roadway grade only.

Problem: Determine legs of sight triangle.

Solution: From the table shown above:

$ISD_a = 165'$

$ISD_b = 115'$

Example 2-6: Intersection Sight Distance – Stop Controlled

Given: Minor road intersects a 4-lane highway with a two-way, left-turn lane (TWLTL).
Minor road is stop controlled.
Design speed of the major highway is 50 mph.
All travel lane widths are 12 feet.
The TWLTL width is 14 feet.
Trucks are not a concern.

Problem: Determine the intersection sight distance (*ISD*) to the left and right from the minor road.

Solution: The following steps will apply:

1. For the vehicle turning right from the minor road, the intersection sight distance (*ISD*) to the left can be determined directly from Appendix F, Exhibit F-11. For the 50-mph design speed, the *ISD* to the left is 480 feet.

2. For the vehicle turning left, the *ISD* must reflect the additional time required to cross the additional lanes. The following will apply:
   a. First, determine the extra width required by the one additional travel lane and the TWLTL and divide this number by 12 feet:

      $(12 + 14) \div 12 = 2.2$ lanes

   b. Next, multiply the number of lanes by 0.5 seconds to determine the additional time required:

      (2.2 lanes) x (0.5 sec/lane) = 1.1 seconds

   c. Add the additional time to the basic gap time of 7.5 seconds and insert this value into Appendix F, Equation F.3-1:

      $ISD = (1.47) \times (50) \times (7.5 + 1.1) = 632'$

      Provide an *ISD* of 635′ to the right for the left-turning vehicle.

3. Check the crossing vehicle, as discussed in Appendix F, Section F.3.2.2. The following will apply:
   a. First determine the extra width required by the two additional travel lanes and the TWLTL and divide this number by 12 feet:

      $\frac{(12 + 12 + 14)}{12} = 3.2$ lanes

b. Next, multiply the number of lanes by 0.5 seconds to determine the additional time required:

(3.2 lanes)(0.5 sec/lane) = 1.6 seconds

c. Add the additional time to the basic gap time of 6.5 seconds and insert this value into Appendix F, Equation F.3-1:

$ISD = (1.47)\ (50)\ (6.5 + 1.6) = 595'$

The 595′ for the crossing maneuver is less than the 635′ required for the left-turning vehicle and, therefore, is not the critical maneuver.

Example 2-7: Decision Sight Distance

Given: A rural two-lane, two-way, level roadway with a design speed of 60 mph.

Problem: Determine the associated avoidance maneuvers for the given roadway and determine the decision sight distances for each of the avoidance maneuvers.

Solution: From the footnotes of Exhibit 2-12: This is a rural facility, the two avoidance maneuvers that address rural roads are A and C.

From Exhibit 2-12: Using the design speed of 60 mph, the decision sight distances for a rural roadway are:

Avoidance Maneuver A: 610 feet
Avoidance Maneuver C: 990 feet

Horizontal Alignment Example Calculations

Example 3-1: Spiral Curve

Given: Rural Two-Lane, Two-Way Highway
Design Speed = 70 mph
Δ = 15°00’00”
(Master) PI Station = 243+18.72
R_c = 3,000 feet
e_{max} = 8%
Refer to Appendix H.1.1 for a diagram of the different elements of a spiral curve and Appendix H.1.2 for the associated definitions for these different elements.

Problem: If a spiral curve is warranted, determine the curve data for the spiral curve.

Solution: The following steps apply:

1. From Chapter 3, Section 3.2.1, a spiral curve is warranted on a rural State highway where the superelevation, *e,* is greater than or equal to 7%. From Chapter 3, Exhibit 3-5, *e* is 7% for *V* = 70 mph and R_c = 3,000 feet, therefore, use a spiral curve.

2. The length of the spiral curve (L_s) is set equal to the superelevation runoff (*L*) length. From Chapter 3, Exhibit 3-5, *L* = 210’ for *V* = 70 mph and *R* = 3,000 feet, therefore, L_s = 210 feet.

3. Calculate the curve parameters by using the spiral curve formulas provided in Appendix H.1.3:
    1. $\theta_S = (L_s / R_C)(90/\pi) = (210/3000)(90/\pi)$
       $\theta_S = 2.00535...°$
       $\theta_S = 2°00'19"$ (rounded value)
    2. $\Delta_C = \Delta - 2\theta_S = (15°00'00") - 2(2°00'19")$
       $\Delta_C = 10°59'22" = 10.9894...°$
       (Note: Rounding to the nearest second requires decimal degrees to the nearest 0.0001.)
    3. $L_C = \frac{\Delta_C}{360} 2\pi \quad R_C = \frac{10.9894}{360}(2\pi)(3000)$
       $L_C = 575.4049...'$
       $L_C = 575.40'$ (rounded value)
    4. $T_S = (R_C + p)\tan(\Delta/2) + k$
    5. $E_S = (R_C + p)\left(\frac{1}{\cos \Delta/2} - 1\right) + p$

6. *Route Location and Design*, Hickerson provides two methods for determining *p* and *k* transition spiral values. The formula method from Hickerson's *Route Location and Design* pg. 375 is shown below;

$$p = L_s\left[0.00145444\ \theta_s - 1.582315\ \theta_s^{\ 3}(10)^{-8} + 1.022426\ \theta_s^{\ 5}(10)^{-13}\ldots\right]$$

$$k = L_s\left[0.5 - 5.076957\ \theta_s^{\ 2}(10)^{-6} + 4.295915\ \theta_s^{\ 4}(10)^{-11}\ldots\right]$$

Calculating using these formulas and the length of spiral and theta calculated above:

$p = 0.612'$ and $k = 104.996'$

Hickerson's *Route Location and Design* also provides Functions of Unit Spiral Length Tables for interpolating unit values p_{unit} and k_{unit}. These are calculated by setting L_s equal to 1, and tabulated for integer values of θ_s. Interpolating from the table p_{unit} = 0.002917 and k_{unit} = 0.49998.

The values above are for a unit spiral length and need to be adjusted for L_s. Multiply the unit values by L_s to obtain the actual values for *p* and *k*.

$p = p_{unit}\ (L_s)$ = (0.002917) (210) = 0.612473′ rounding $p = 0.612'$

$k = k_{unit}\ (L_s)$ = (0.49998) (210) = 104.995713′ rounding $k = 104.996'$

Therefore:

T_s = (3000 + 0.612) tan (15/2) + 104.996′

T_s = 500.034'

T_s = 500.03′ (rounded value)

E_s = (3000 + 0.612) (1/cos(15/2) - 1) + 0.612′

E_s = 26.504′

E_s = 26.50′(rounded value)

7. Determine the Stations for TS, SC, CS and ST:

TS Station = PI Station - T_s = [243+18.72] - 500.03′ = 238+18.69

SC Station = TS Station + L_s = [238+18.69] + 210′ = 240+28.69

CS Station = SC Station + L_c = [240+28.69] + 575.40′ = 246+04.09

ST Station = CS Station + L_s = [246+04.09] + 210′ = 248+14.09

Example 3-2: Circular Curve

Given: Δ = 7°00′00″

R = 5,700 feet

e_{max} = 8%

PI Station = 154+56.42

Design Speed = 60 mph

Refer to Appendix H.2.1 for a diagram of the different elements of a circular curve and Appendix H.2.2 for the associated definitions for these different elements.

Problem: According to Chapter 3, Section 3.2.1 use a circular curve when the superelevation is less than 7%. From Chapter 3, Exhibit 3-5, e is 3% for V = 60 mph and R = 5700′, therefore, use a circular curve. Calculate the curve parameters by using the circular curve formulas provided in Appendix H.2.3.

Solution: The following steps apply:

1. Calculate the Tangent Distance:

$$T = R(\tan(\Delta / 2)) = 5700(\tan(7 / 2))$$

$$T = 348.6269'$$

$$T = 348.63' \text{ (rounded value)}$$

2. Calculate the Length of Curve:

$$L = \frac{\Delta}{360} 2\pi R = \frac{7}{360}(2\pi)(5700)$$

$$L = 696.3863'$$

$$L = 696.39' \text{ (rounded value)}$$

3. Calculate the External Distance:

$$E = \frac{R}{\cos(\Delta / 2)} - R = \frac{5700}{\cos(7 / 2)} - 5700$$

$$E = 10.6515'$$

$$E = 10.65' \text{ (rounded value)}$$

4. Length of Long Chord:

$$LC = 2R(\sin(\Delta / 2)) = (2)(5700)(\sin(7/2))$$

$$LC = 695.9533'$$

$$LC = 695.95' \text{ (rounded value)}$$

5. Calculate the Middle Ordinate:

$$M = R(1 - \cos(\Delta / 2)) = 5700(1 - \cos(7/2))$$

$$M = 10.6316'$$

$$M = 10.63' \text{ (rounded value)}$$

6. Stations are as follows:

PC Station = PI Station - T = [154+56.42] - 348.63′ = 151+07.79

PT Station = PC Station + L = [151+07.79] + 696.39′ = 158+04.18

Example 3-3: Reverse Curve Superelevation Transition - Continuously Rotating Plane between Two Circular Curves

Given: A two-lane, two-way, rural roadway with a design speed of 45 mph and the following reverse curves (circular):

Curve 1	Curve 2
PI Station = 27+27.45	PI Station = 46+47.67
Δ = 73° 08' 53" RT	Δ = 61° 14' 40" LT
R = 1,800 feet	*R* = 1,050 feet
PC Station = 13+91.92	PC Station = 40+26.15
PT Station = 36+89.94	PT Station = 47+92.30

Problem: Calculate the reverse curve superelevation transition, assuming a continuously rotating plane, between the two circular curves.

Solution:

1. Determine if the curves meet the criteria for superelevation transition by the continuous rotating plane method.

From Chapter 3, Exhibit 3-5**:**

Curve 1 requires a 5% superelevation (*e*1), with 110′ of Runoff (*L*1), and 44′ of Tangent Runout (*TR*1) for normal superelevation development.

Curve 2 requires a 7% superelevation (*e*2), with 154′ of Runoff (*L*2), and 44′ of Tangent Runout (*TR*2) for normal superelevation development.

The tangent distance between the two curves is:

PC2 Sta. – PT1 Sta. = [40+26.15] – [36+89.94] = 336.21′

The distance outside of the curves required for normal superelevation development is 70% of the runoff for each curve + the runout distances. For these curves, normal superelevation transitions between the curves would require:

$0.7 \times (L1 + L2) + TR1 + TR2 = 0.7 \times (110.00' + 154.00') + 2 \times 44' = 272.80'$

The length of normal crown between transitions is 336.21′ – 272.80′ = 63.41′. The *TR* distance for all superelevated curves with a design speed of 45 mph is 44′. The length of normal crown section provided (63.41′) is less than twice the *TR* distance (2 x 44′ = 88′) and therefore, it is not desirable to attain a normal crown section. The continuously rotating plane method is applicable in this situation.

Note that the minimum tangent distance between these two curves would be 70% of the two runoff distances, or 184.80′. Any tangent distance less than this would require either an increase in the normal transition rate or locating more of the transitions on the curves if the curves cannot be moved further away from each other. Either option requires approval of the Highways Engineer as documented in the Alignment and Grade Review Report (AGR Report).

2. Locate the stations of full superelevation.

For continuous rotating plane transitions, the points of full superelevation are held and the transitions are combined into a continuous transition with a constant rate of change.

Points of full super elevation are determined normally, that is 30% of the standard runoff distances onto each curve.

The point where the superelevation starts to transition from 5% RT (point A on the exhibit below) is:

Station A = PT1 station – 0.3(*L*1) = [36+89.94] – 0.3 x (110.00′) = Sta. 36+56.94

The point where the transition ends at full 7% superelevation LT (point C on the exhibit below) is:

Station C = PC2 station + 0.3(L2) = [40+26.15] + 0.3 x (154.00′) = Sta. 40+72.35

3. Determine the location of level roadway (point B on the exhibit below).

The total length of continuous superelevation transition (L_{REV}) is the distance between points A and C.

L_{REV} = Station C – Station A = [40+72.35] – [36+56.94] = 415.41′

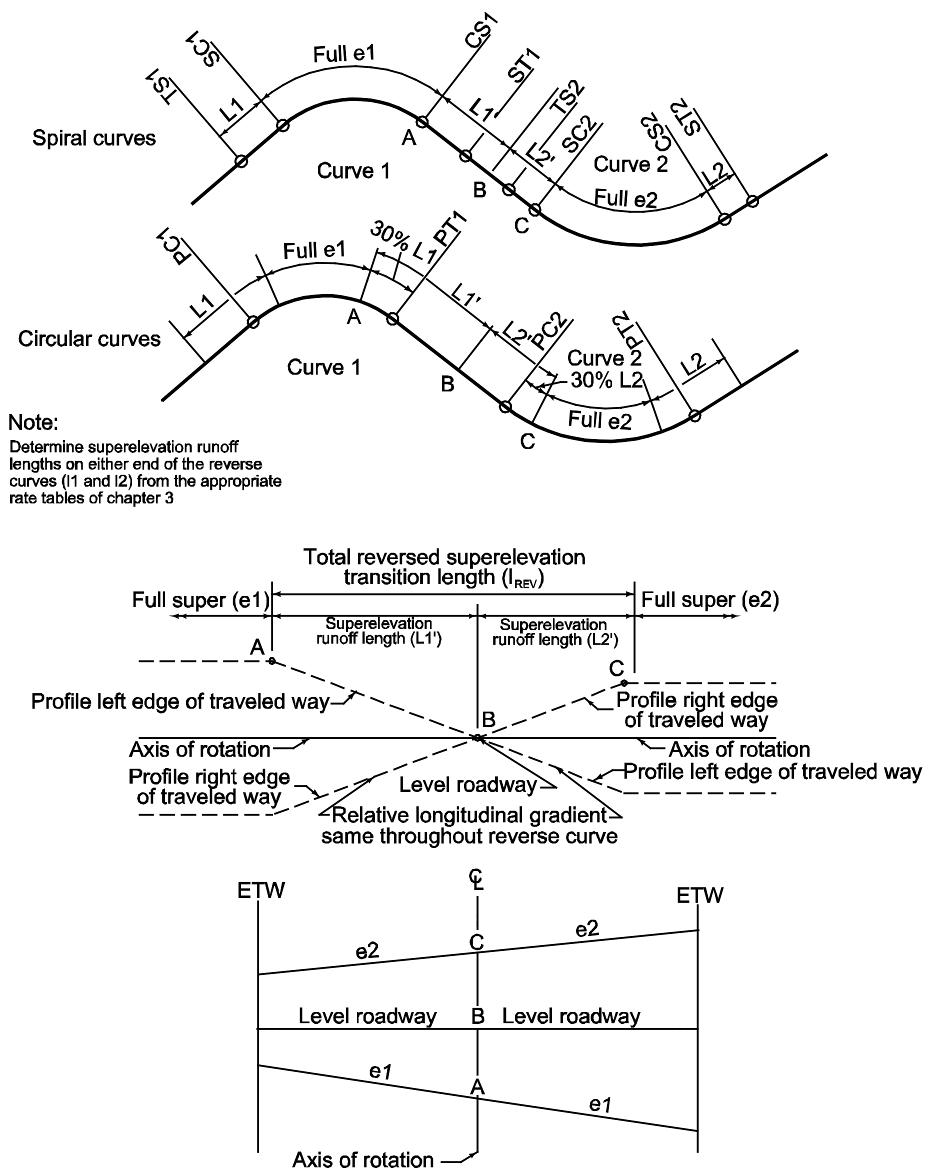
The length of superelevation transition from 5% RT to level (*L1′*) is the distance between points A and B.

$$L1' = \frac{e1}{(e1+e2)} \times L_{REV} = \frac{5}{(5+7)} \times 415.41' = 173.09'$$

Station B = Station A + *L1′* = [Station 36+56.94] + 173.09 = 38+30.03

L2′ can either be determined by subtracting Station B from Station C, or from the following equation:

$$L2' = \frac{e2}{(e1+e2)} \times L_{REV} = \frac{7}{(5+7)} \times 415.41' = 242.32'$$



For checking the superelevation at a given station (point *X*) within the transition, identify whether the location is within *L1′* or *L2′*. If the station is less than Station B, it falls within L1′; otherwise, it is within *L2′*.

$$e_x = \frac{\text{Station B} - \text{Station X}}{L1'} \times e1 \quad \text{or} \quad \frac{\text{Station X} - \text{Station B}}{L2'} \times e2$$

Determining the superelevation at a point can be useful in checking rollover and the effect of cross slope on approach turning movements, drainage or other cross slope critical criteria, and elevation/clearance for overhead structures.

In this example, if one wanted to determine the superelevation at Station 37+20.00:

37+20.00 is less than 38+30.03, therefore is located within the *L1′* section.

$$e = \frac{[38+30.03]-[37+20.00]}{173.09'} \times 5\% \text{ RT} = 3.18\% \text{ RT (rounded)}$$

Example 3-4: Reverse Curve Superelevation Transition - Continuously Rotating Plane between Two Curves with Spiral Transitions

Given: A four-lane, two-way, open roadway with a design speed of 55 mph and the following reverse curves (w/ spiral transition):

Curve 1	Curve 2
PI Station = 314+76.54 Δ = 23° 30' 00" LT R = 1,150 feet	PI Station = 323+93.50 Δ = 21° 18' 00" RT R = 1,500 feet

Problem: Calculate the reverse curve superelevation transition, using a continuously rotating plane between the two curves with spiral transitions.

Solution:

1. Determine if the curves meet the criteria for superelevation transition by the continuous rotating plane method.

   From Chapter 3, Exhibit 3-6**:**

   Curve 1 requires an 8% superelevation ($e1$), with 312′ of Runoff ($L1$) which will coincide with the Spiral Transition ($L1 = Ls1$), and 78′ of Tangent Runout ($TR1$) for normal superelevation development.

   Curve 2 requires a 7% superelevation ($e2$), with 273′ of Runoff ($L2$) which will coincide with the Spiral Transition ($L2 = Ls2$), and 78′ of Tangent Runout ($TR2$) for normal superelevation development.

   Using spiral formulas found in Appendix H.1.3, the following parameters are calculated:

Curve 1	Curve 2
PI Station = 314+76.54	PI Station = 323+93.50
Δ = 23° 30' 00" LT	Δ = 21° 18' 00" RT
R = 1,150'	R = 1,500'
L_s = 312'	L_s = 273'
θ_s = 7° 46' 20"	θ_s = 5° 12' 50"
p = 3.52464'	p = 2.06964'
k = 155.90436'	k = 136.46233'
T_s = 395.84'	T_s = 418.92'
Δ_c = 7° 57' 20"	Δ_c = 10° 52' 20"
L_c = 159.68'	L_c = 284.63'
TS Station = 310+80.70	TS Station = 319+74.58
SC Station = 313+92.70	SC Station = 322+47.58
CS Station = 315+52.38	CS Station = 325+32.21
ST Station = 318+64.38	ST Station = 328+05.21

   The tangent distance between the two curves is:
   TS2 Sta. – ST1 Sta. = [319+74.58] – [318+64.38] = 110.20′

The distance outside of the curves required for normal superelevation development is the sum of the Tangent Runout distances:

$TR1 + TR2 = 78.00' + 78.00' = 156.00'$

The length of normal crown between transitions is 110.20′ – 156.00′ = -45.80′. This distance is less than 2 times the *TR* length (2 x 78′ = 156′), and the continuous rotating plane method is applicable in this situation.

2. Locate the stations of full superelevation.

For continuous rotating plane transitions, the points of full superelevation are held and the transitions are combined into a continuous transition with a constant rate of change.

The points of full superelevation are the SC and CS of each curve, with the entire circular curve section between these points at the full superelevation. The end of full 8% LT (point A on the exhibit below) is the CS of Curve 1, Station 315+52.38 and the SC of Curve 2, Station 322+47.58 is the beginning of full 7% super RT (point C on the exhibit below).

3. Determine the location of level roadway (point B on the exhibit below).

The total length of continuous superelevation transition (L_{REV}) is the distance between points A and C.

L_{REV} = Station C – Station A = [322+47.58] – [315+52.38] = 695.20′

The length of superelevation transition from 8% LT to level (*L1′*) is the distance between points A and B.

$$L1' = \frac{e1}{(e1+e2)} \times L_{REV} = \frac{8}{(8+7)} \times 695.20' = 370.77'$$

Station B = Station A + *L1′* = [315+52.38] + 370.77′ = 319+23.15

This point is not identified in the plans specifically, except in the cross sections, but it indicates where the roadway surface drainage changes, and is helpful in determining the cross slope at any point within the transition. From 319+23.15 the roadway drains left to right back on station, and drains right to left ahead on station.

L2′ can be calculated similarly:

$$L2' = \frac{e2}{(e1+e2)} \times L_{REV} = \frac{7}{(8+7)} \times 695.20' = 324.43'$$

For checking the superelevation at a given station (point *X*) within the transition, identify whether the location is within *L1′* or *L2′*. If the station is less than Station B, it falls within *L1′*; otherwise, it is within *L2′*.

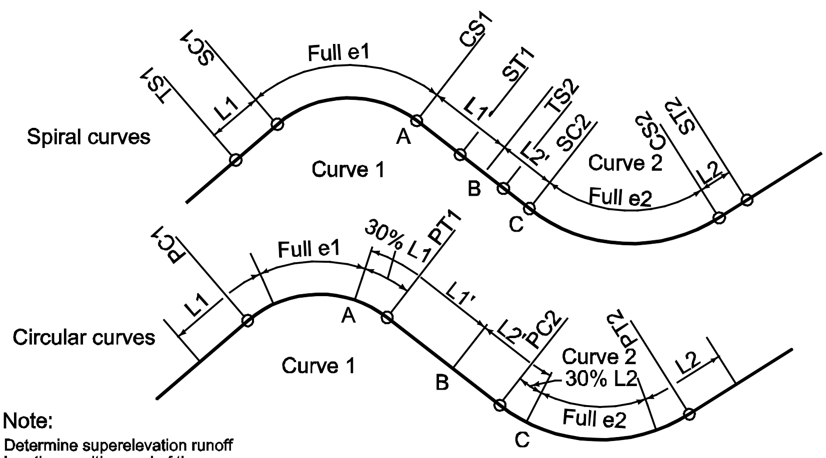
$$e_x = \frac{\text{Station B} - \text{Station X}}{L1'} \times e1 \quad \text{or} \quad \frac{\text{Station X} - \text{Station B}}{L2'} \times e2$$

Determining the superelevation at a point can be useful in checking rollover and the effect of cross slope on approach turning movements, drainage or other cross slope critical criteria, and elevation/clearance for overhead structures.

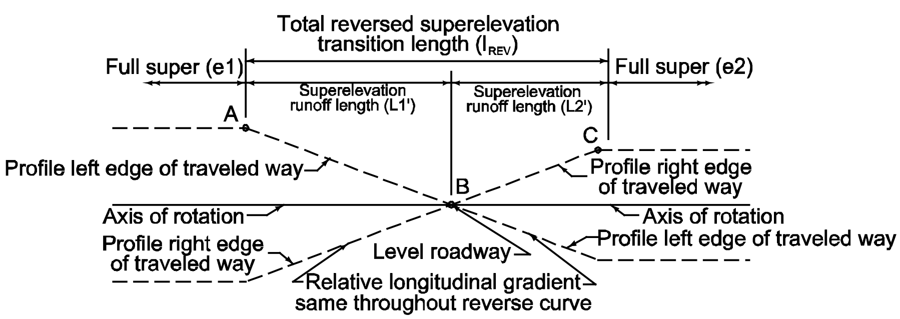
In this example, if one wanted to determine the superelevation at Station 321+00.00:

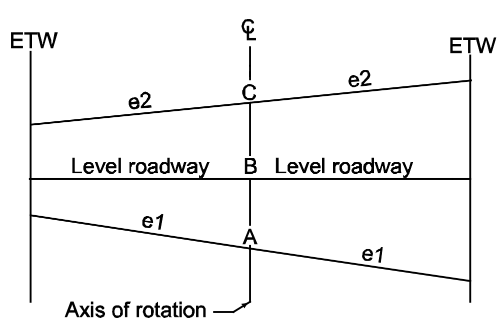
321+00.00 is greater than 319+23.15, therefore is located within the *L2′* section.

$$e = \frac{[321+00.00]-[319+23.15]}{324.43'} \times 7\% \ \text{RT} = 3.82\% \ \text{RT (rounded)}$$



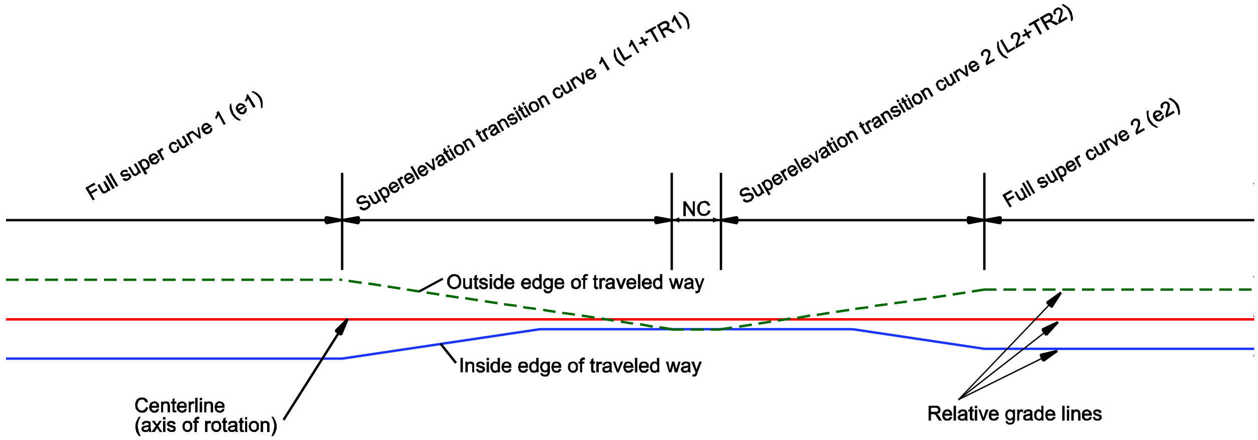
Note:
Determine superelevation runoff lengths on either end of the reverse curves (l1 and l2) from the appropriate rate tables of chapter 3





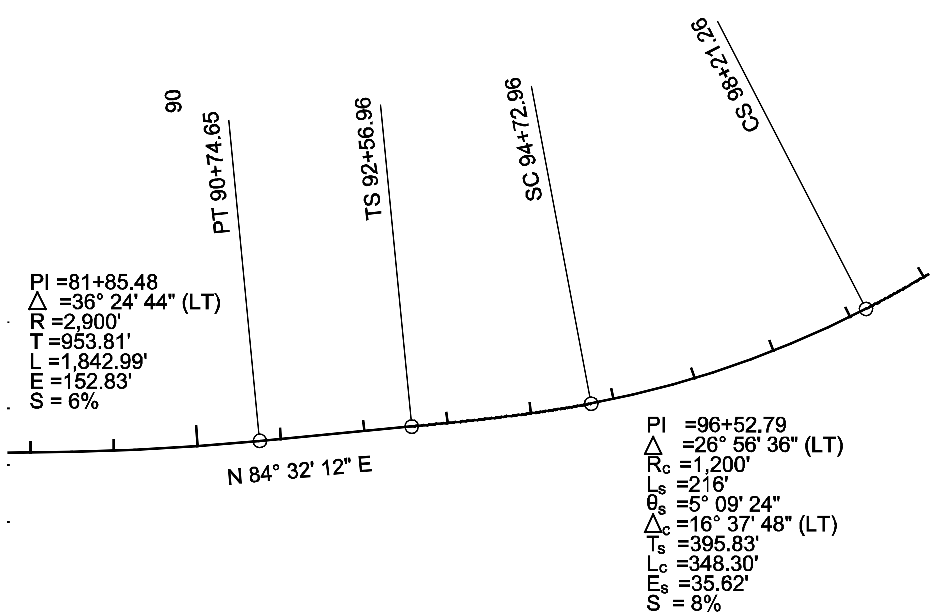
Example 3-5: Broken Back Curve Application

Given: Superelevation transition for horizontal curves in the same direction (broken-back curves). The exhibit below represents the relative grade lines of each edge of the traveled way for a roadway transitioning through two superelevated curves in the same direction:



When the standard transition lengths result in a normal crown (NC) section between the curves less than 200 feet long, do not transition down to normal crown. Instead, transition down to a section with less superelevation, but not less than the normal crown cross slope that can be maintained for at least 200 feet.

Problem: Given the following alignment, determine the superelevation transition between the curves assuming a 60 mph design speed, two-lane, two-way roadway rotated about the centerline, and a normal crown of 2 percent:



Solution:

1. Determine the normal transition lengths and locations for each curve.

   For a design speed of 60 mph, Exhibit 3-5 indicates that 27 feet of transition length is needed for each 1 percent change in cross slope.

   The first curve is circular, with 6 percent superelevation. For circular curves, 30 percent of the runoff length is located on the curve:

   Start of transition (6%) = [PT station] – 0.3(*L*) = [90+74.65] – 0.3(162′) = Sta. 90+26.05

   End of transition (NC) = [90+26.05] + *L* + *TR* = [90+26.05] + 162′ + 54′ = Sta. 92+42.05

   For the second curve, the 8 percent runoff length is applied through the corresponding spiral transition length (216 feet). The tangent runout distance (54 feet) back from the TS station is the station where normal crown would end, and the transition to 8 percent superelevation begins:

   Start of transition (NC) = [TS station] – *TR* = [92+56.96] – 54′ = Sta. 92+02.96

   End of transition (8%) = [SC station] = Sta. 94+72.96

2. Check the length of normal crown between transitions:

   Length of NC provided = [92+02.96] - [92+42.05] = –39.09′

   If the length of NC section provided is 200 feet or more, standard transitions may be provided. Otherwise, proceed on to Step 3. (A negative value, as in this case, indicates the distance that the transition locations overlap each other.)

3. Determine the intermediate rate of superelevation that can be held for at least 200 feet between transitions using the following equation:

$$S' = \frac{200' - \text{length of NC provided (feet)}}{2 \times \text{length for } 1\% \text{ change (feet)}} - NC$$

where:

S′ = intermediate percent superelevation

NC = normal crown cross slope

$$S' = \frac{200' - (-39.09')}{2 \times 27'} - 2 = \frac{239.09'}{54'} - 2 = 2.43\text{, round} \Rightarrow 3\%$$

Note: Round up to the next integer value equal to or greater than the normal crown cross slope (2% is typical for paved roadways).

4. Determine the stations within the transitions where the superelevation is 3 percent:

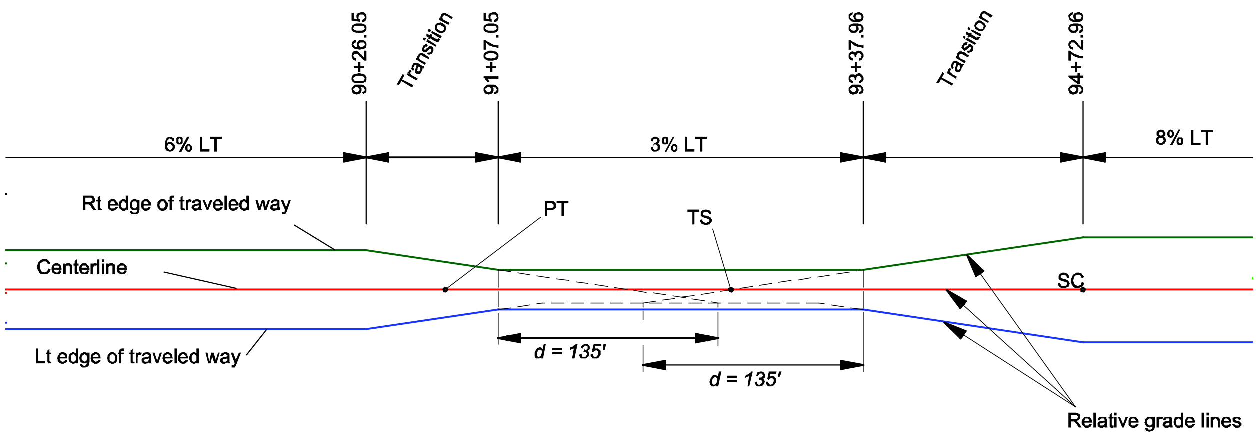
   Working from the end of each transition where NC would be provided, the distance, d, to the 3 percent superelevated section is calculated:

$$d = (S' + \text{NC}) \text{ x length for 1\% change (feet)} = (3 + 2) \text{ x } 27' = 135'$$

   Station of start of constant 3% = [92+42.05] - 135′ = Sta. 91+07.05

   Station of end of constant 3% = [92+02.96] + 135′ = Sta. 93+37.96

   The figure below represents the relative grade lines for the edge of traveled way for this example.



   These transitions would be indicated in the plans by the stationing callouts on the superelevated typical section, rather than transitioning back and forth between typicals.

   For example:

XX+XX.XX to 90+26.05	6% LT
90+26.05 to 91+07.05	Trans. 6% LT to 3% LT
91+07.05 to 93+37.96	3% LT
93+37.96 to 94+72.96	Trans. 3% LT to 8% LT
94+72.96 to YY+YY.YY	8% LT

Example 3-6: Compound Curve Application

Given: $\Delta = 40°$
$R1 = 600$ feet
$R2 = 250$ feet
$p = 5'$
Refer to Appendix H.3.1 for a diagram of the different elements of a compound curve.

Problem: Determine the curve data for the compound curve.

Solution: Use the compound curve formulas from Appendix H.3.2 to calculate the curve parameters:

1. $T_1 = (R_2 + p)\tan(\Delta/2) = (250'+5')\tan(40°/2)$

   $T_1 = 92.81'$

2. $$\Delta_1 = \cos^{-1}\left[\frac{R_1 - R_2 - p}{R_1 - R_2}\right] = \cos^{-1}\left[\frac{600'-250'-5'}{600'-250'}\right]$$

   $\Delta_1 = 9.6963°$

   $\Delta_1 = 9°41'47''$ (rounded value)

3. $T = T_1 + (R_1 - R_2)\sin\Delta_1 = 92.81' + (600'-250')\sin(9.6963°)$

   $T = 151.7591'$

   $T = 151.76'$ (rounded value)

4. $T_2 = T_1 - R_2 \sin\Delta_1 = 92.81' - (250')\sin(9.6963°)$

   $T_2 = 50.7036'$

   $T_2 = 50.70'$ (rounded value)

5. $$E = \frac{R_2 + p}{\cos(\Delta/2)} - R_2 = \frac{250'+5'}{\cos(40°/2)} - 250'$$

   $E = 21.3653'$

   $E = 21.37'$ (rounded value)

6. $M = R_2 - (R_2 \cos\ (\Delta / 2 - \Delta_1)) = 250' - \left(250' \cos\left(\frac{40°}{2} - 9.6963°\right)\right)$

$M = 4.0316'$

$M = 4.03'$ (rounded value)

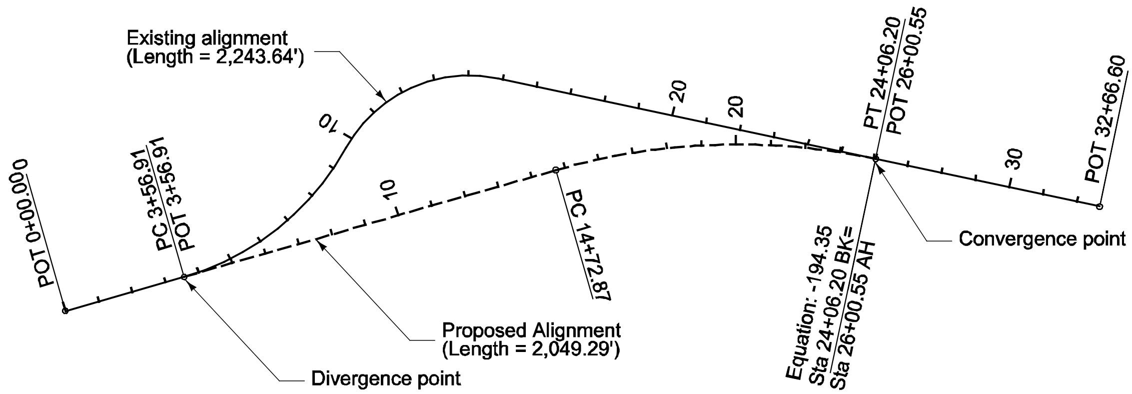
7. $y = (R_2 + p) - R_2 \cos \Delta_1 = (250' + 5') - (250') \cos(9.6963°)$

$y = 8.5714'$

$y = 8.57'$ (rounded value)

Example 3-7: Station Equation Applications – Negative (Gap) Equation

Given: An existing compound curve is reconstructed with a proposed simplified alignment:



Problem: The proposed alignment reduces the overall length of the alignment, creating a stationing discrepancy at the end of the project. Determine a station equation to correct the stationing discrepancy.

Solution: Determine the negative (gap) station equation as follows:

1. Determine Back (BK) Station

   BK Sta. = Divergence Sta. + Proposed Alignment Length
   BK Sta. = [3+56.91] + 2,049.29′
   BK Sta. = 24+06.20

2. Determine Ahead (AH) Station

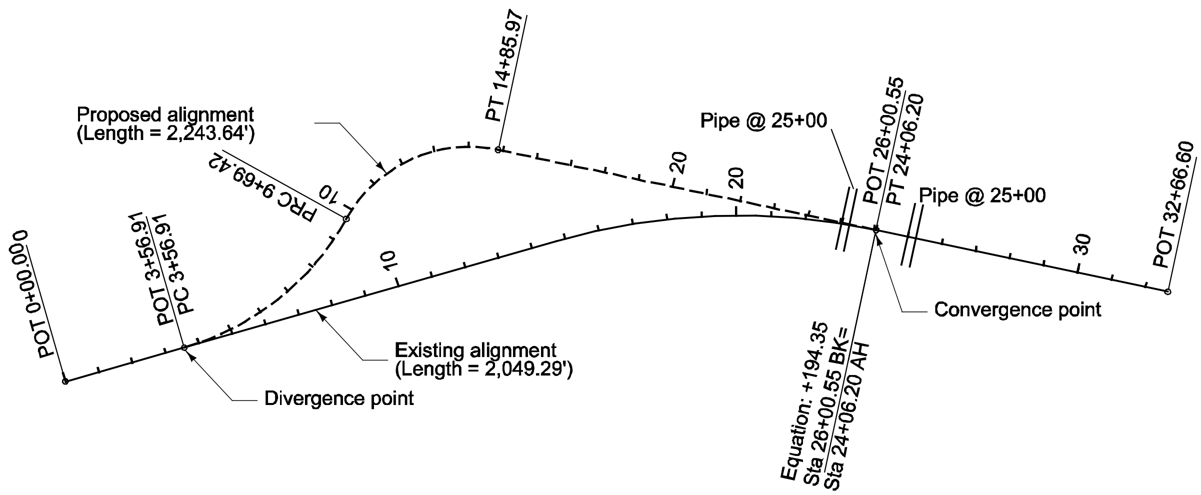
   AH Sta. = Divergence Sta. + Existing Alignment Length
   AH Sta. = [3+56.91] + 2,243.64′
   AH Sta. = 26+00.55

3. Determine Station Equation

   Sta. Equation = BK Sta. – AH Sta.
   Sta. Equation = [24+06.20] – [26+00.55]
   Sta. Equation = -194.35′

Example 3-8: Station Equation Applications – Positive (Overlap) Equation

Given: An existing alignment is reconstructed with a proposed reverse curve:



Problem: The proposed alignment increases the overall length of the alignment, creating a stationing discrepancy at the end of the project. Determine a station equation to correct the stationing discrepancy.

Solution: Determine the positive (overlap) station equation as follows:

1. Determine Back (BK) Station

   BK Sta. = Divergence Sta. + Proposed Alignment Length
   BK Sta. = [3+56.91] + 2,243.64′
   BK Sta. = 26+00.55

2. Determine Ahead (AH) Station

   AH Sta. = Divergence Sta. + Existing Alignment Length
   AH Sta. = [3+56.91] + 2,049.29′
   AH Sta. = 24+06.20

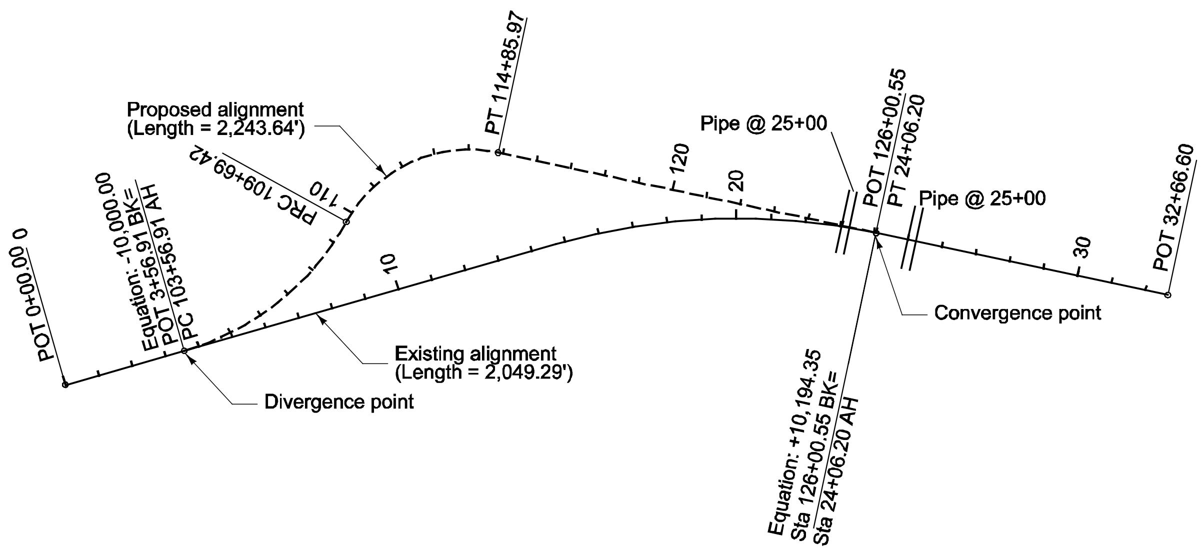
3. Determine Station Equation

   Sta. Equation = BK Sta. – AH Sta.
   Sta. Equation = [26+00.55] – [24+06.20]
   Sta. Equation = +194.35′

Note: This scenario can create an undesirable condition where project features can have coincident stations (see culverts in figure above for example). See the following example for a solution to this condition.

Example 3-9: Station Equation Applications – Alternate Stationing

Given: An existing alignment is reconstructed with a proposed reverse curve:



Problem: The proposed alignment increases the overall length of the alignment, creating a stationing discrepancy at the end of the project. Determine alternate stationing for the proposed alignment to correct the stationing discrepancy and to avoid coincident stations.

Solution: Determine the alternate stationing and station equation as follows:

1. Establish Alternate Alignment Ahead (AH) Stationing at Divergence

   AH Sta. = Divergence BK Sta. – Sta. Equation
   AH Sta. = [3+56.91] – (-10,000.00')
   AH Sta. = 103+56.91

2. Determine Back (BK) Station at Convergence

   BK Sta. = Divergence AH Sta. + Proposed Alignment Length
   BK Sta. = [103+56.91] + 2,243.64'
   BK Sta. = 126+00.55

3. Determine Ahead (AH) Station at Convergence

   AH Sta. = Divergence BK Sta. + Existing Alignment Length
   AH Sta. = [3+56.91] + 2,049.29'
   AH Sta. = 24+06.20

4. Determine Station Equation at Convergence

Sta. Equation = Convergence BK Sta. – Convergence AH Station
Sta. Equation = [126+00.55] – [24+06.20]
Sta. Equation = +10,194.35′

Note: This scenario corrects the undesirable condition where project features can have coincident stations (see culverts in figure above for example). See the previous example describing the undesirable condition.

Vertical Alignment Example Calculations

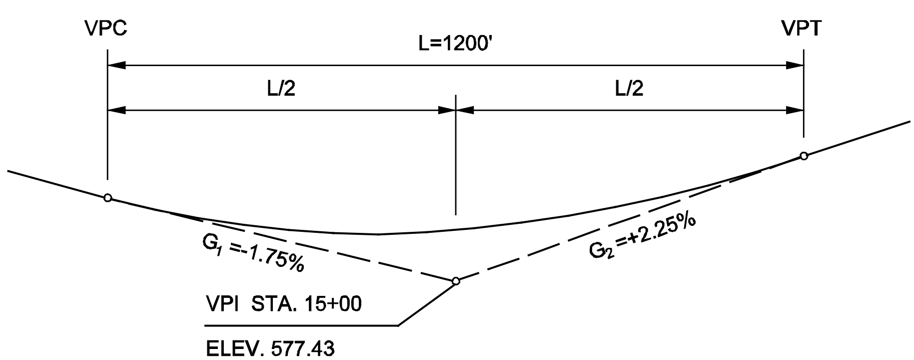
Example 4-1: Compute Elevations and Stations at Specific Points on a Symmetrical Sag Vertical Curve

Given: G_1 = -1.75%
G_2 = +2.25%
Elevation of VPI = 577.43′
Station of VPI = 15+00
L = 1,200′
Symmetrical Vertical Curve
Refer to Appendix H.4.1 for a diagram of the different elements of a symmetrical vertical curve and Appendix H.4.2 for the associated definitions for these different elements.

Problem: Compute the vertical curve elevations for each 50-foot station. Compute the low point elevation and stationing.

Solution: The following steps apply:

1. Draw a diagram of the vertical curve and determine the station at the beginning (VPC) and the end (VPT) of the curve.



VPC Station = VPI Sta. – ½ L = [15+00] – (0.5)(1200′) = 9+00
VPT Station = VPI Sta. + ½ L = [15+00] + (0.5)(1200′) = 21+00

2. Use the symmetrical vertical curve formulas from Appendix H.4.3 to calculate the elements of the vertical curve:

$$CURVE\,ELEV. = TAN.ELEV. + Z$$

Where:

Left of VPI (X_1 measured from VPC):	Right of VPI (X_2 measured from VPT):
(a) $TAN\ \ ELEV. = VPC\,ELEV. + G_1\left(\frac{X_1}{100}\right)$	(a) $TAN\ \ ELEV. = VPT\,ELEV. - G_2\left(\frac{X_2}{100}\right)$
(b) $Z_1 = X_1^2\,\frac{(G_2 - G_1)}{200\,L}$	(b) $Z_2 = X_2^2\,\frac{(G_2 - G_1)}{200\,L}$

3. Set up a table to show the vertical curve elevations at the 50-foot stations, substituting the values into the above equations.

Station	Inf.	Tangent Elevation	*X*	X^2	$Z=X^2/60{,}000$[1]	Grade Elevation
9+00	VPC	587.930	0	0	0	587.93
9+50		587.055	50	2,500	0.0417	587.10
10+00		586.180	100	10,000	0.1667	586.35
10+50		585.305	150	22,500	0.3750	585.68
11+00		584.430	200	40,000	0.6667	585.10
11+50		583.555	250	62,500	1.0417	584.60
12+00		582.680	300	90,000	1.5000	584.18
12+50		581.805	350	122,500	2.0417	583.85
13+00		580.930	400	160,000	2.6667	583.60
13+50		580.055	450	202,500	3.3750	583.43
14+00		579.180	500	250,000	4.1667	583.35
14+50		578.305	550	302,500	5.0417	583.35
15+00		577.430	600	360,000	6.0000	583.43
15+50		578.555	550	302,500	5.0417	583.60
16+00		579.680	500	250,000	4.1667	583.85
16+50		580.805	450	202,500	3.3750	584.18
17+00		581.930	400	160,000	2.6667	584.60
17+50		583.055	350	122,500	2.0417	585.10
18+00		584.180	300	90,000	1.5000	585.68
18+50		585.305	250	62,500	1.0417	586.35
19+00		586.430	200	40,000	0.6667	587.10
19+50		587.555	150	22,500	0.3750	587.93
20+00		588.680	100	10,000	0.1667	588.85
20+50		589.805	50	2,500	0.0417	589.85
21+00	VPT	590.930	0	0	0	590.93

[1] The 60,000 value is calculated according to $200L/(G_2\text{-}G_1)$ → (200*1,200)/(2.25 – (-1.75)) = 60,000.

4. Calculate the low point on the curve:

To determine distance "X_T" from VPC: $X_T = \frac{LG_1}{G_1 - G_2}$

$$X_T = \frac{LG_1}{G_1 - G_2} = \frac{1200'(-1.75)}{-1.75 - 2.25} = \frac{-2{,}100.00'}{-4.00} = 525.00' \text{ from } VPC$$

To determine low point stationing: $VPC\,Sta. + X_T$

Therefore, the Station at the low point is:

$$VPC_{STA} + X_T = [9 + 00] + (525') = 14 + 25$$

To determine the low point elevation on the vertical curve:

$$ELEV_{LOW\ POINT} = ELEV\ VPC - \frac{LG_1^2}{(G_2 - G_1)200}$$

Elevation of the low point on the curve equals:

$$Elev.VPC - \frac{LG_1^2}{(G_2 - G_1)200} = 587.93' - \frac{1{,}200'(-1.75)^2}{(2.25 - (-1.75))200} = 583.34'$$

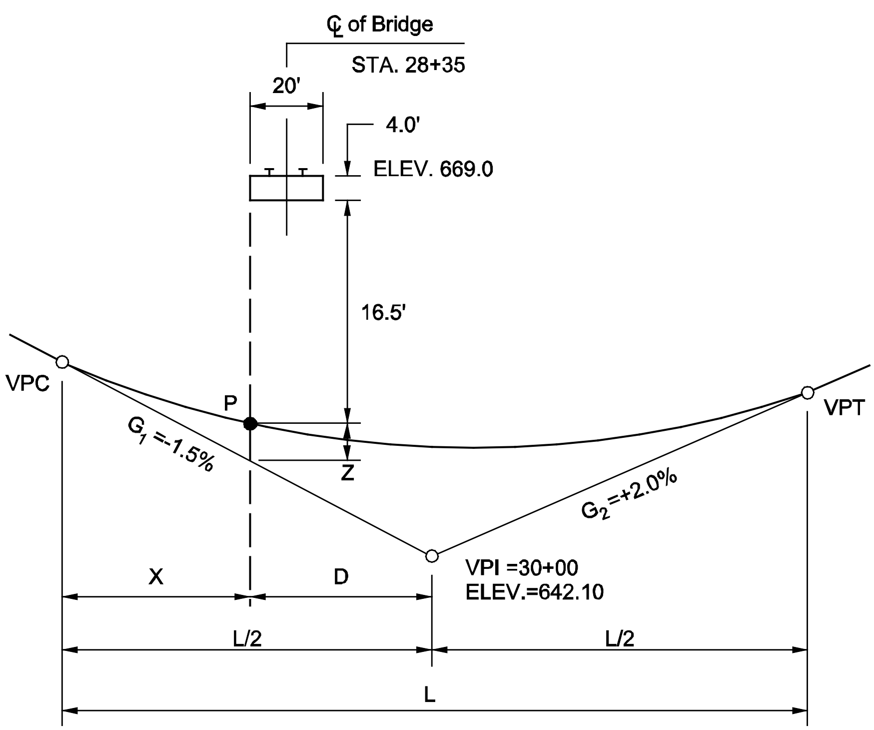
Example 4-2: Symmetrical Vertical Curve Through a Fixed Point

Given: Design Speed = 55 mph
G_1 = -1.5%
G_2 = +2.0%
VPI Station = 30+00
VPI Elevation = 642.10′
Refer to Appendix H.4.1 for a diagram of the different elements of a symmetrical vertical curve and Appendix H.4.2 for the associated definitions for these different elements.

Problem: At Station 28+35, the new highway must pass under the center of an existing railroad which is at elevation 669.00′ at the highway centerline. The railroad bridge that will be constructed over the highway will be 4.0′ in depth, 20.0′ in width and at right angles to the highway. What would be the length of the symmetrical vertical curve that would provide a 16.5′ clearance under the railroad bridge?

Solution:

1. Sketch the problem with known information labeled.



2. Determine the station where the minimum 16.5′ vertical clearance will occur (Point P):

   From inspection of the sketch, the critical location appears to be on the left side of the railroad bridge. The critical station is:

$$STA.\ P = BRIDGE\ CENTERLINE\ STATION - \frac{1}{2}(BRIDGE\ WIDTH)$$

$$STA.\ P = [28+35] - \frac{20'}{2}$$

$$STA.\ P = 28+25$$

3. Determine the elevation of Point P:

   ELEV. P = ELEV. TOP RAILROAD BRIDGE – BRIDGE DEPTH - CLEARANCE

$$ELEV.\ P = 669.00' - 4.00' - 16.50'$$

$$ELEV.\ P = 648.50'$$

4. Determine distance, *D*, from Point P to VPI:

$$D = STA.\ VPI - STA.\ P$$
$$= [30+00] - [28+25]$$
$$= 175'$$

5. Determine the tangent elevation at Point P:

$$TAN.\ ELEV.\ AT\ \ P = ELEV.\ VPI - G_1\left(\frac{D}{100}\right)$$
$$= 642.10 - (-1.5)\left(\frac{175}{100}\right)$$
$$= 644.73'$$

6. Determine the vertical curve correction (*Z*) at Point P:

$$Z = ELEV.\ P - TAN.\ ELEV.$$
$$= 648.50' - 644.73'$$
$$= 3.77'$$

7. Solve for *X* using the following equation:

$$X = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a}$$

where:

X = Horizontal Distance: Measured from the VPC (or VPT) to any point on the vertical curve (feet)

$a = A$ = Algebraic Difference in Grade: The difference between the two tangent grades (G_1-G_2) (percent)

$b = Z$ = Tangent Offset: The vertical distance from the tangent line to any point on the vertical curve (feet)

$c = D \times Z$ = Product of D (distance from the VPI to the subject point, P) and Z (tangent offset) (square feet)

$$X = \frac{400Z \pm \sqrt{160{,}000Z^2 + 1{,}600ADZ}}{2A}$$

$$X = \frac{400(3.77) \pm \sqrt{160{,}000(3.77)^2 + 1{,}600(3.5)(175)(3.77)}}{2(3.5)}$$

$$X = 564.44' \quad AND \quad X = -133.58' \ (Disregard)$$

8. Using either of the following equations, solve for L:

$$X + D = L/2 \quad or \quad L = 2(X + D)$$

$$L = 2(X + D)$$
$$L = 2(564.44' + 175')$$
$$L = 1{,}478.88'$$

9. Check the critical point assumption from Step 2. Since the sketch is based on an assumed length of curve, the low point of the curve is also at an assumed location. In this example, the tangent grades of the curve are not “sketched” correctly. They indicate that the low point of the curve is on the right side of the VPI. In fact, the low point is on the left side of the VPI, as the magnitude of G_1 is less than that of G_2.

Using the equation for finding the low point of the curve (see example 4-1): $X_T = \frac{LG_1}{G_1 - G_2}$

$$X_T = \frac{LG_1}{G_1 - G_2} = \frac{1478.88'(-1.50)}{-1.50 - 2.00} = \frac{-2{,}218.32'}{-3.50} = 633.81' \text{ from } VPC$$

The station of the low point of the sag is 28+94.37, which is on the right side of the center of the railroad bridge station of 28+35.00. Therefore, the critical point assumption made in Step 2 is confirmed. Proceed to the next step.

Note: If the low point station had been on the left side of the bridge centerline, the length of curve required for clearance would need to be recalculated for the correct critical location on the right side of the bridge. Completing the sketch as accurately as possible for the known elements will lessen the likelihood of assuming the incorrect critical point, particularly for cases where the overhead structure is much wider.

10. Determine if the solution meets the desirable stopping sight distance for the 55 mph design speed. From Exhibit 4-5, the desirable K-value:

    $K = 115$

    The algebraic difference in grades:

    $A = G_2 - G_1 = (+2.0) - (-1.5) = 3.5$

    From Equation 4.4-9, the minimum length of vertical curve which meets the desirable stopping sight distance:

    $$\begin{aligned} L_{MIN} &= KA \\ &= (115) \times 3.5 \\ &= 402.5' \end{aligned}$$

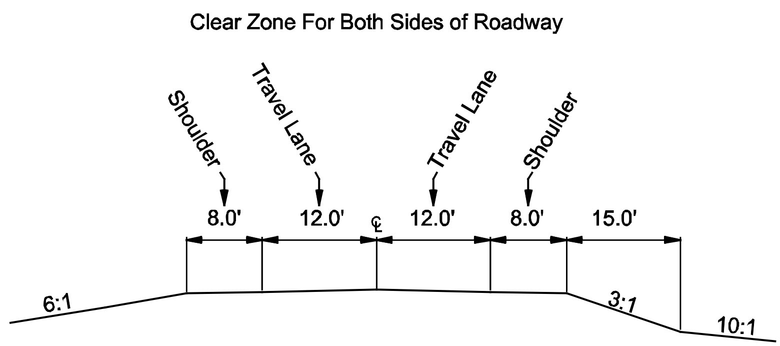
    Therefore, L = 1,478.88′ will provide the desirable stopping sight distance.

    Note: This would be rounded down to 1,450′ for recording on the plans.

Roadside Safety Example Calculations

Example 9-1: Clear Zone for Both Sides of the Roadway

Given: Design Speed = 55 mph
Annual Average Daily Traffic (AADT) = 4,750
Lane Width: 12 feet
Shoulder Width: 8 feet



Problem: Determine the clear zone distance for both sides of the roadway.

Solution: Using the procedure in Chapter 9, Section 9.2.2.2 for each side of the roadway:

1. For the left side of the roadway, the entire slope is flatter than 4:1, so the clear zone can be determined directly from Exhibit 9-1.

   Left Clear Zone Width = 20 feet (Exhibit 9-1)

2. For the right side of the roadway, the 3:1 slope is non-recoverable. The procedure in Chapter 9, Section 9.2.2.2, Step 2 must be used.

3. Checking the recovery area beyond the toe, the slope of 10:1 is flatter than 4:1. This 10:1 slope is then used to determine the clear zone distance required from Exhibit 9-1.

   Right Clear Zone Width = 20 feet (Exhibit 9-1)

4. The recovery area beyond the toe is calculated by subtracting the 8 feet of recoverable slope between the edge of traveled way and the hinge point from the 20 feet obtained in Step 3:

   20′ – 8′ = 12′ Distance beyond the toe

5. Since 12′ > 10′, 12′ will be used as the recovery distance beyond the toe. (Chapter 9, Section 9.2.2.2, Step 2c)

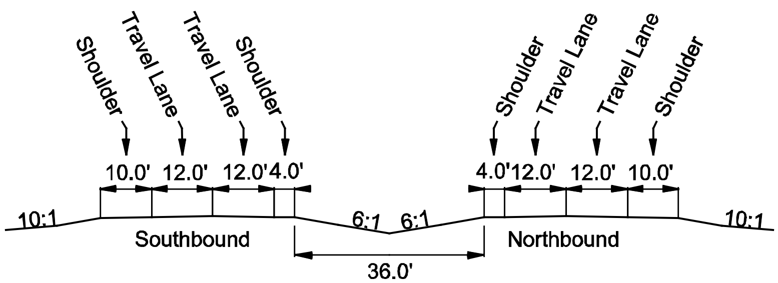
6. Using the 12 feet recovery distance beyond the toe, the total clear zone width is calculated by summing the distance beyond the toe and the distance from the edge of traveled way to the toe:

   8′ + 15′ + 12′ = 35′ Total Right Clear Zone Width

Example 9-2: Clear Zone for a Divided Highway

Given: Design Speed: 70 mph
AADT: 18,000
Lane Width: 12 feet
Outside Shoulder Width: 10 feet
Inside Shoulder Width: 4 feet
Median Width: 36 feet

Clear Zone For a Divided Highway



(Not to Scale)

Problem: Determine the clear zone distances.

Solution: Using the procedure in Chapter 9, Section 9.2.2.2 for each side of each roadway:

1. For the outside in each direction of travel, the slope is flatter than 4:1, so the clear zone can be determined directly from Exhibit 9-1:

   Outside Clear Zone Width = 32 feet (Exhibit 9-1)

2. In the median, for the inside in each direction of travel, the inslope of 6:1 is flatter than 4:1, so a clear zone distance can be obtained from Exhibit 9-1:

   Median Clear Zone Width = 32 feet (Exhibit 9-1)

3. The toe of the backslope is located at the center of the median which is 22 feet (4’ + 18’) from each inside edge of traveled way.

   22’ < 32’, so the toe is within the clear zone.

4. Since the toe is within the clear zone, the median toe must be checked for traversability. Using Exhibit 9-10, the median is determined to be traversable.

5. The percentage of the clear zone available up to the toe of the backslope is computed:
   22′ ÷ 32′ = 0.6875

6. This value is subtracted from Step 2 and multiplied by the adjusted backslope clear zone factor of 30 feet obtained from Exhibit 9-6:
   (1 - 0.6875) x 30′ = 9.38′ (Clear zone distance required beyond the toe)

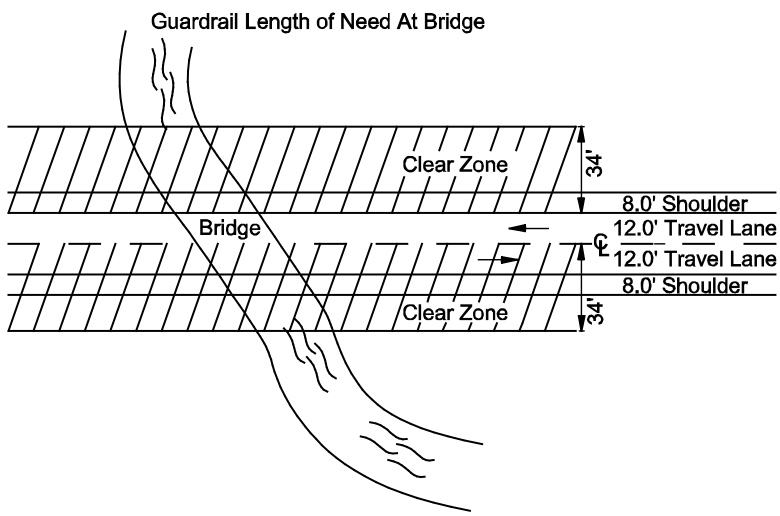
7. The total clear zone is obtained by adding the value from Step 6 and the distance to the toe:

   9.38′ + 22′ = 31.38′

8. This value is rounded up to the next foot, yielding a Total Median Clear Zone Width of 32 feet.

Example 9-3: Guardrail Length of Need for Obstacle Extending Beyond the Clear Zone

Given: Design Speed: 55 mph
AADT: 4,750
Shoulder Width: 8 feet
Lane Width: 12 feet
Clear Zone Width: 34 feet
Non-flared Guardrail (flared guardrail not allowed) with face of rail at edge of shoulder



Problem: Determine the length of need for guardrail on each side of the road on this end of the bridge (obstacle extends to the edge of the clear zone).

Solution:

1. Using Exhibit 9-16 the runout length is obtained by linear interpolation between 50 and 60 mph:

   (160′ + 210′) ÷ 2 = 185′

2. A non-flared design will be used, Equation 9.4-2 is applied.

   $$X = \frac{L_R(L_O - L_1)}{L_O}$$

   a. For a departure to the right:

      L_R = 185 feet
      L_O = L_C = 34 feet
      L_1 = 8 feet

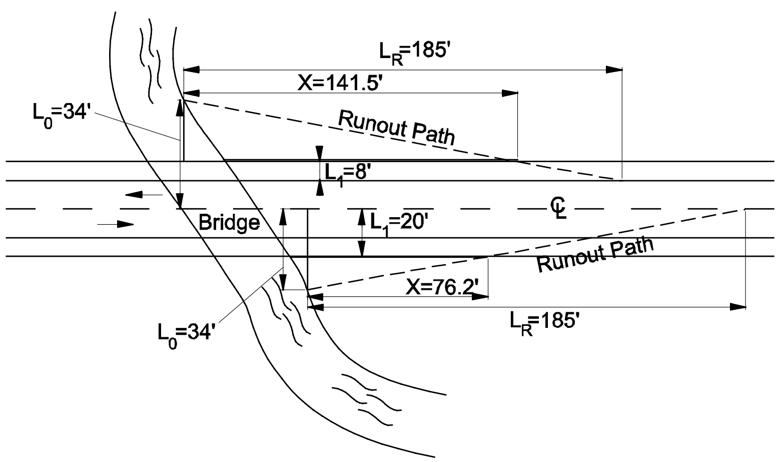
      X = [185′ x (34′ - 8′)] ÷ 34′ = 141.5′ Length of Need

b. For a departure to the left:

L_R = 185 feet
L_O = L_C = 34 feet
L_1 = 12′ + 8′ = 20 feet

X = [185′ x (34′ - 20′)] ÷ 34′ = 76.2′ Length of Need

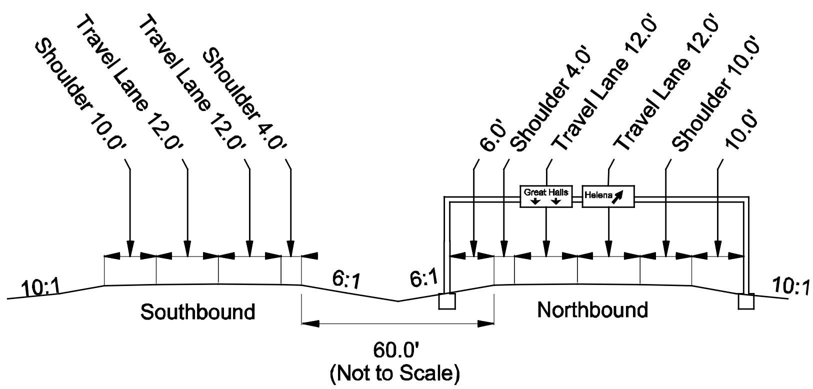
NOTE: Some of the length of need will be covered by terminal end sections and the bridge approach section. These lengths should be determined before computing the final length of rail required for each side.

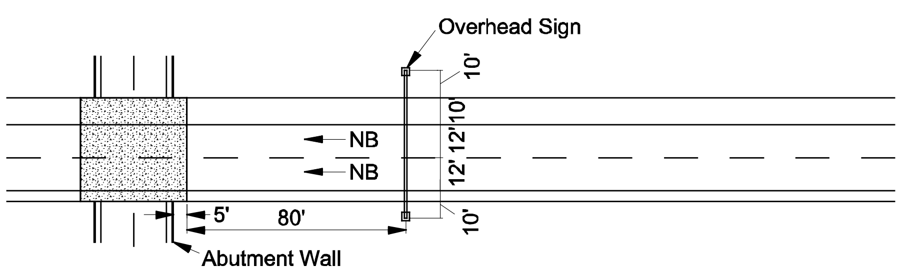


Example 9-4: Controlling Length of Need for Multiple Obstacles

Given: Design Speed: 70 mph
AADT: 18,000
Outside Shoulder Width: 10 feet
Inside Shoulder Width: 4 feet
Lane Width: 12 feet
Clear Zone Width: 32 feet
Non-Flared Guardrail

Guardrail Length of Need for Bridge and Overhead Sign





Problem: Determine if the bridge or the sign controls the barrier length and find the length of need for guardrail on each side of the NB side of the highway.

Solution:

1. Using Exhibit 9-16 the runout length is determined to be 360 feet.

2. A non-flared design will be used. Equation 9.4-2 will be used to compute length of need.

3. For a left side departure:

   a. The length of need for the sign support is computed as follows:
   L_R = 360 feet
   L_O = 4′ + 6′ = 10 feet (hazard is within the clear zone)
   L_1 = 4 feet

   X = [360′ x (10′ - 4′)] ÷ 10′ = 216.0′ Length of Need

   b. The length of need for the bridge abutment wall is computed as follows:

   L_R = 360 feet
   L_O = L_C = 32 feet (hazard extends beyond the clear zone)
   L_1 = 4 feet

   X = [360′ x (32′ - 4′)] ÷ 32′ = 315.0′ Length of Need

   c. Guardrail must extend at least 315 feet from the abutment wall and 216 feet from the sign support. Adding 216 feet to the 85 feet from the abutment wall to the sign support gives 301 feet, which is less than 315 feet, so the bridge drop-off is the controlling feature and the final length of need is 315 feet from the abutment wall.

4. For a right side departure:

   a. The length of need for the sign support is computed as follows:

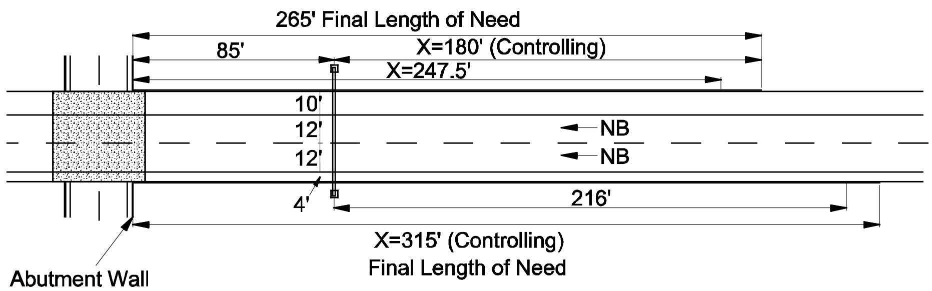
   L_R = 360 feet
   L_O = 10′ + 10′ = 20 feet
   L_1 = 10 feet

   X = [360′ x (20′ - 10′)] ÷ 20′ = 180.0′ Length of Need

   b. The length of need for the bridge abutment wall is computed as follows:
   L_R = 360 feet
   L_O = L_C = 32 feet (hazard extends beyond the clear zone)
   L_1 = 10 feet

   X = [360′ x (32′ - 10′)] ÷ 32′ = 247.5′ Length of Need

c. Guardrail must extend at least 247.5 feet from the abutment wall and 180 feet from the sign support. Adding 180 feet to the 85 feet from the abutment wall to the sign support gives 265 feet, which is greater than 247.5 feet, so the sign is the controlling feature and the final length of need is 265 feet from the abutment wall.



Example 9-5: Minimum Length of Culvert

Background: The length of large culverts with concrete edge protection must be long enough so that the top portion of concrete edge protection is out of the clear zone. This is typically straightforward on culverts that are perpendicular to the roadway. However, when drawing culverts on a skew, make sure that the skewed corners of the concrete edge protection are out of the clear zone.

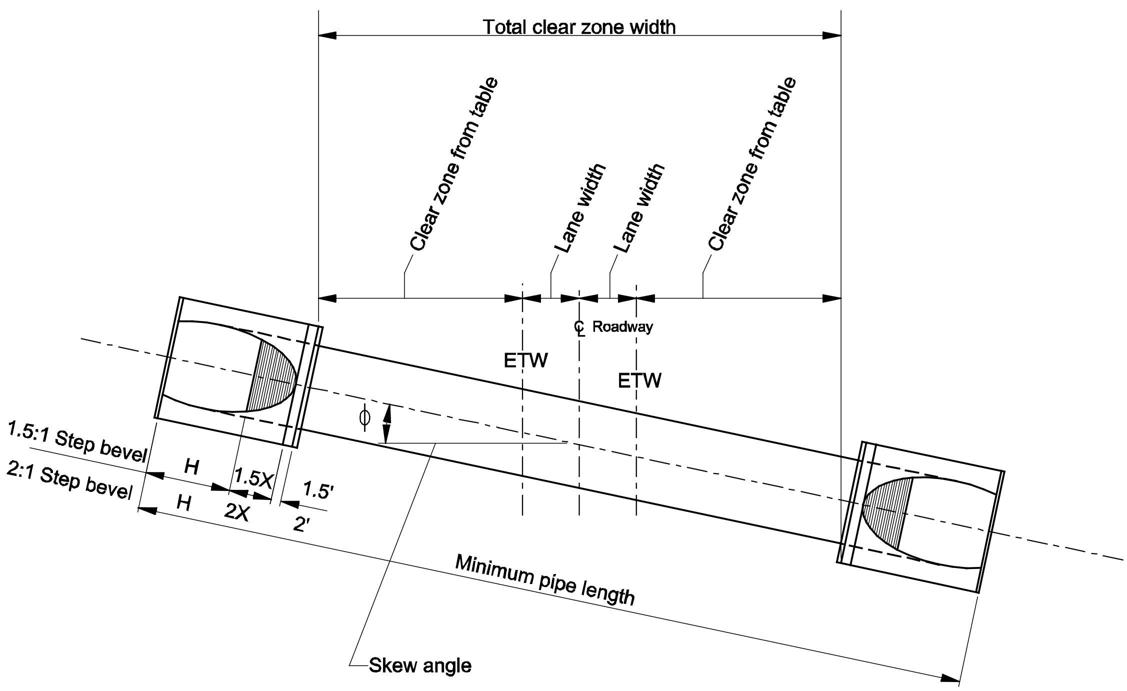
Use the following formulas to calculate the minimum lengths of skewed culverts to ensure that the concrete edge protection is out of the clear zone:

1.5:1 Step Bevel Formula:

$$\frac{(\sin\phi\,(0.5D + 4') \times 2 + \text{Total Clear Zone Width})}{\cos\phi} + (1.5' + 1.5X + H) \times 2 = \text{min. pipe length}$$

2:1 Step Bevel Formula:

$$\frac{(\sin\phi\,(0.5D + 4') \times 2 + \text{Total Clear Zone Width})}{\cos\phi} + (2' + 2X + H) \times 2 = \text{min. pipe length}$$



Given: 18' Diameter Circular Metal Pipe

ϕ = 12 degree skew

2:1 Step Bevel Ends with Concrete Edge Protection on Inlet and Outlet

Clear Zone Distance from ETW = 36'

2 lane roadway with 12' lanes

Culvert Dimensions from Detailed Drawings:

D = 18'

X = 4.5'

H = 18'

Problem: Determine the minimum overall length of culvert to make sure that the concrete edge protection is out of the clear zone.

Solution:

2:1 Step Bevel Formula:

$$\frac{(\sin\phi\,(0.5D + 4') \times 2 + \text{Total Clear Zone Width})}{\cos\phi} + (2' + 2X + H) \times 2 = \text{min. pipe length}$$

$$\frac{(\sin 12°\,((0.5 \times 18') + 4') \times 2 + (36' + 12' + 12' + 36'))}{\cos 12°} + (2' + (2 \times 4.5') + 18') \times 2$$
$$= \text{min. pipe length}$$

$$\frac{(0.2079 \times 13') \times 2 + 96')}{0.9781} + (29' \times 2) = \text{min. pipe length}$$

$$\frac{101.4054'}{0.9781} + 58' = \text{min. pipe length}$$

= 161.68', round to 162'

Quantity Summaries Example Calculations

SYMMETRICAL SECTIONS BACKGROUND

Section 13.5.1.1 provides an overview of symmetrical sections that is the most commonly used typical section for determining the horizontal dimensions of various surface courses. The first step is to establish the width of subgrade using the following equation:

$$W_S = W_f + \left(\frac{tZ}{1-CZ}\right)$$

where:

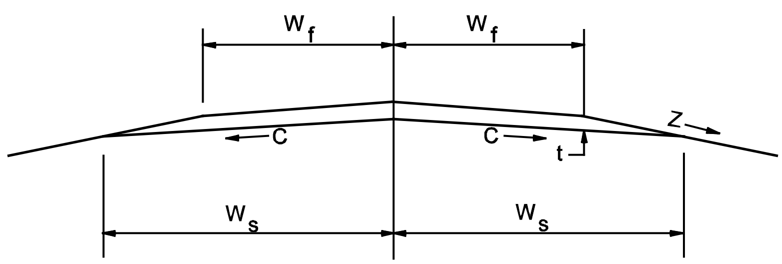
W_S = half width of subgrade, feet

W_f = half width of finished grade, feet

t = total surfacing thickness at finished shoulder, feet

Z = numerator of side slope ratio
(e.g., Z = "6" for a 6:1 side slope)

C = crown, feet/feet (e.g., 0.02 for 2% cross slope)



Round the computed value for W_s to the nearest 0.1′. Because of the rounding process, the side slope through the surfacing courses will not be exactly 6:1, but the difference is negligible.

The second step is to establish the width of the intermediate surfacing courses. Compute each horizontal course dimension proportionately to its thickness. The width at the top of any surfacing course is determined by using the following equation:

$$W_X = W_f + \left[\frac{(W_S - W_f)}{t}\right] t_X$$

where:

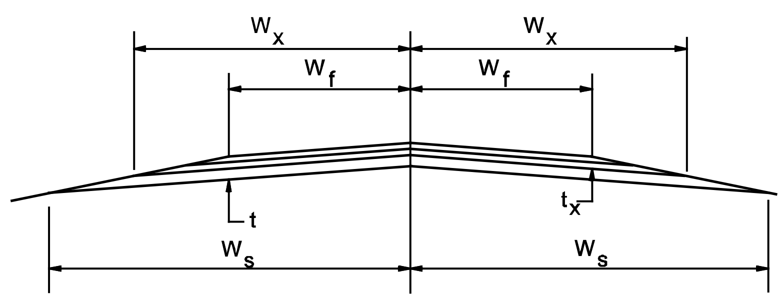
W_X = half width of top of intermediate surfacing course, feet

W_f = half width of finished grade, feet

W_S = half width of subgrade, feet

t = total surfacing thickness at finished shoulder, feet

t_X = cumulative thickness of courses above W_X at finished shoulder, feet



Round the computed value for W_X to the nearest 0.1′.

Example 13-1: Symmetrical Sections – Width of Subgrade

Given: W_f = 20.0 feet
t = 1.80 feet
Z = 6:1
C = 0.02

Problem: Determine the half width of subgrade.

Solution:

1. Use the following equation and solve for W_s.

$$W_S = W_f + \left(\frac{tZ}{1-CZ}\right)$$

$$W_S = 20.0' + \frac{(1.8')(6)}{1-(0.02)(6)}$$

$$W_S = 20.0' + 12.27' = 32.27'$$

$W_S = 32.3'$ (Rounded to nearest 0.1 foot)

The second step is to establish the width of the intermediate surfacing courses, which is shown in more detail in Example 13-2.

Example 13-2: Symmetrical Sections – Intermediate Surface Width

Given: $t_x = 0.80'$

Problem: Using the values given in Example 13-1, determine the intermediate surfacing course half width.

Solution:

1. Use the following equation and solve for W_X.

$$W_X = W_f + \left[\frac{(W_S - W_f)}{t}\right] t_X$$

$$W_X = 20.0' + \left[\frac{(32.3' - 20.0')}{1.8'}\right] 0.80'$$

$$W_X = 20.0' + 5.467' = 25.467'$$

$W_X = 25.5'$ (Rounded to nearest 0.1′)

UNSYMMETRICAL SECTIONS BACKGROUND

Section 13.5.1.2 provides an overview of unsymmetrical sections that compute and record the widths to the left and right of centerline separately for determining the horizontal dimensions of various surface courses.

Superelevated Sections.

To compute subgrade widths for superelevated sections, use the equations shown below:

Low Side

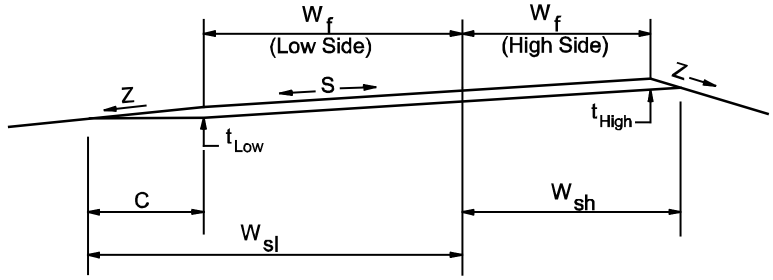
$$W_{sl} = W_f + \frac{tZ}{1 - CZ}$$

High Side

$$W_{sh} = W_f + \frac{tZ}{1 + SZ}$$

where:

W_{sl} = width from centerline to edge of subgrade on low side of superelevation, feet
W_{sh} = width from centerline to edge of subgrade on high side of superelevation, feet
W_f = width from centerline of finished grade, low or high side, feet
t = total thickness of surfacing at finished shoulder, feet
S = slope of superelevation, feet/feet (e.g., 0.07 for 7% superelevation)
Z = numerator of side slope ratio (e.g., Z = "6" for a 6:1 side slope)
C = cross slope of tangent typical section, feet/feet (e.g., 0.02 for 2% cross slope)



Round each computed value for W_{sl} and W_{sh} to the nearest 0.1'.

Divided Highways.

For both tangent and curved sections of divided highways, compute the subgrade widths left and right of centerline as follows:

Tangent

$$W_S(median) = W_f(median) + \frac{tZ}{1-CZ}$$

$$W_S(outside) = W_f(outside) + \frac{tZ}{1-CZ}$$

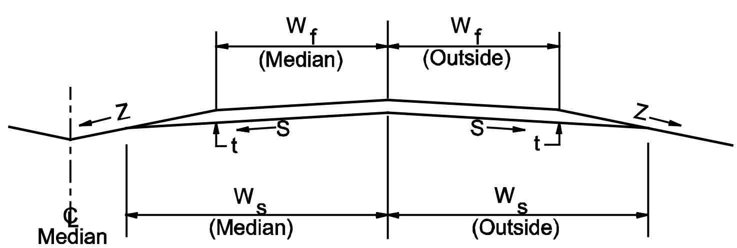
Curve

$$W_S(median\ high\ side) = W_f(median) + \frac{tZ}{1+SZ}$$

$W_S(outside\ low\ side) =$ same as tangent typical section width

$$W_S(outside\ high\ side) = W_f(outside) + \frac{tZ}{1+SZ}$$

$W_S(median\ low\ side) =$ same as tangent typical section width



Round all computed subgrade half widths to the nearest 0.1′.

Intermediate (High Side).

Compute the widths of intermediate surfacing courses for unsymmetrical sections on the high side in the same manner as for symmetrical sections (i.e., proportionately to the thicknesses), except that the width should be computed and recorded separately for each side of the centerline and rounded to the nearest 0.1′.

Intermediate (Low Side).

The following example (Example 13-3) illustrates the procedure that should be used to determine the widths for the intermediate surface courses on the low side of superelevated curves:

Example 13-3: Unsymmetrical Sections – Intermediate Surface Widths

Given:

t = 1.80 feet
t_{x1} = 0.30 feet
t_{x2} = 0.50 feet
W_S = 32.3 feet
W_f = 20.0 feet
Superelevation rate = 8%
Subgrade shoulder slope = 2%

Problem: Determine the widths for the intermediate surface lifts.

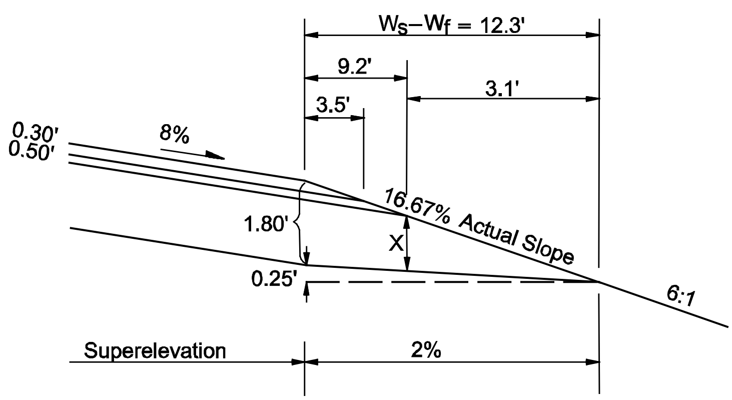
Solution:

1. Determine the actual slope rate.

   Subgrade shoulder width = W_S - W_f = 12.3′
   Rise of subgrade = 12.3′ x 0.02 = 0.246′ ≈ 0.25′
   Total depth = 0.25′ + 1.80′ = 2.05′
   Actual slope = 2.05′ ÷ 12.3′ = 0.1667, or 16.67%
   (Rounded to the nearest 0.01%)

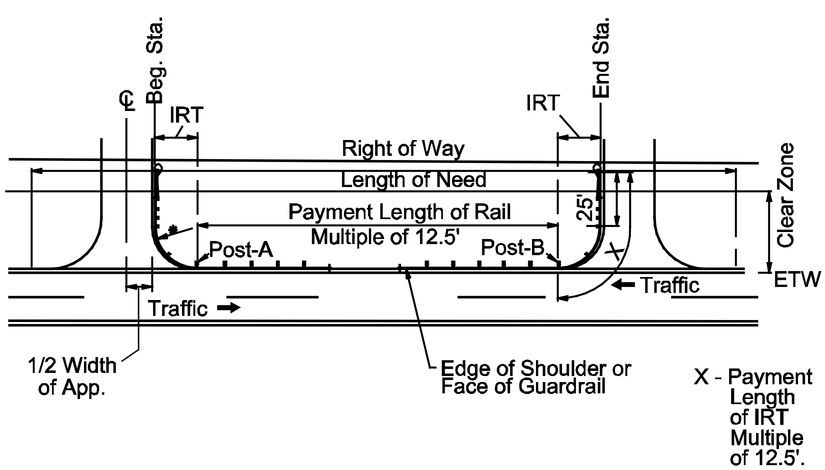
2. Determine horizontal distance for intermediate lifts.

   Slope difference = (16.67 - 8.00) ÷ 100 = 0.0867
   t_{x1} ÷ slope difference = 0.30′ ÷ 0.0867 = 3.46′ ≈ 3.5′
   (t_{x1} + t_{x2}) ÷ slope difference = (0.30′ + 0.50′) ÷ 0.0867 = 9.23′ ≈ 9.2′



GUARDRAIL QUANTITIES BACKGROUND

1. All w-beam, box beam, and cable guardrail runs are measured by the length of feet, exclusive of terminal sections or transitions. One-way departures, Optional Terminal Sections (OTS), Intersecting Roadway Terminals (IRT), and all transitions (including Bridge Approach Sections) are measured per each.
2. Lengths of w-beam guardrail should be rounded up to 12.5-foot increments, and the length of each OTS is 50 feet.
3. Lengths of box beam guardrail should be rounded up to 18-foot increments, and the length of each box beam OTS is 48.2 feet.
4. Lengths of three-strand, low tension cable rail is rounded to the nearest 0.1′ per rounding criteria, and the length of each terminal section is 26 feet. There is no standard increment for normal cable rail, although the maximum post spacing will be 16 feet or 12 feet, depending on roadway curvature. The maximum length of a run (distance between terminal sections) of low tension cable rail is 2000 feet, however multiple runs can be combined to shield longer distances. See the *MDT Detailed Drawings* for layout diagram.
5. All one-way departure sections, and low tension cable terminal sections are located entirely outside the length of need. See the *MDT Detailed Drawings* for the length of need limits within Optional Terminal Section pay limits.
6. Rounding of guardrail to standard lengths will result in lengths of full strength rail that are greater than the measured length of need. When connecting to a fixed location, such as the end of a bridge rail, the stationing called out for guardrail will need to be established based on the bridge rail stationing. For other applications, providing the additional length to the advancement side of the adjacent traffic may be the best practice, however the location of approaches or other roadside features may dictate the optimum location. So long as the entire length of need is protected by full strength rail, and the rail length is at a standard increment, the end stations are not critical for these installations.
7. If approaches, turnouts or other obstacles are within the required length of w-beam guardrail, IRT terminals may be used to shorten the required length. IRTs do not meet all current crash testing requirements, and should only be used as a best practical remaining alternative where fully compliant roadside hardware cannot address a guardrail warrant.



a. Ensure that the right-of-way width is sufficient (i.e., far enough from the shoulder to get the full IRT installed without encroaching onto private property). The width required from the edge of the roadway (face of rail) to the R/W line is equal to the IRT radius + 26.5 feet.

b. Determine the best fit IRT radius based on the approach radii, R/W availability, and the location requirements of the normal run of w-beam. Minor adjustments to the approach stationing or minor grading along the edge of the approach may be necessary to fit the IRT to the approach without impacting turning movements or extending beyond the R/W limit.

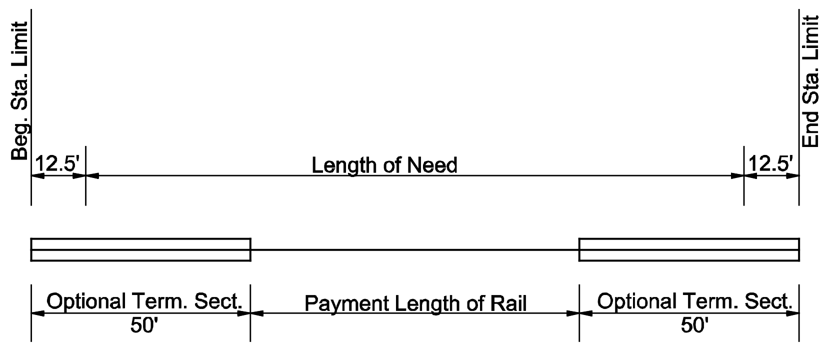
c. The end anchors are included in the IRT bid item.

d. The following table lists available IRT radii and associated pay limits:

Radius	Length of Bent Rail	Total Length of IRT (pay limits)
8’	12.5’	37.5’
16’	25.0’	50.0’
24’	37.5’	62.5’
32’	50.0’	75.0’

Example 13-4: W-Beam Guardrail

Given: W-beam guardrail is warranted between Stations 9+90 and 15+00 on the left side of a two-way roadway. There are no roadway approaches or other features that influence the guardrail location.



Problem: Determine the beginning and ending stations and the length of rail for payment.

Solution:

1. [15+00.00] – [9+90.00] = 510.00′ actual length of need

2. 510.00′ ÷ 12.5′/section = 40.8 sections, Round ⇒ 41

3. 41 x 12.5′ = 512.50′ Length of need based on minimum standard increment

4. Per the detailed drawings, 37.5′ of each OTS provides full strength for length of need.

5. 512.50′- 2(37.50′) = 437.5′ length of standard run rail

6. In this case, no features have been identified to restrict guardrail placement. Locate the guardrail to provide the additional length on the advancement side of the adjacent traffic. Since the rail is on the left side of the roadway, adjacent traffic is moving opposite the direction of increasing stationing, therefore start the calculation from the lower station value:

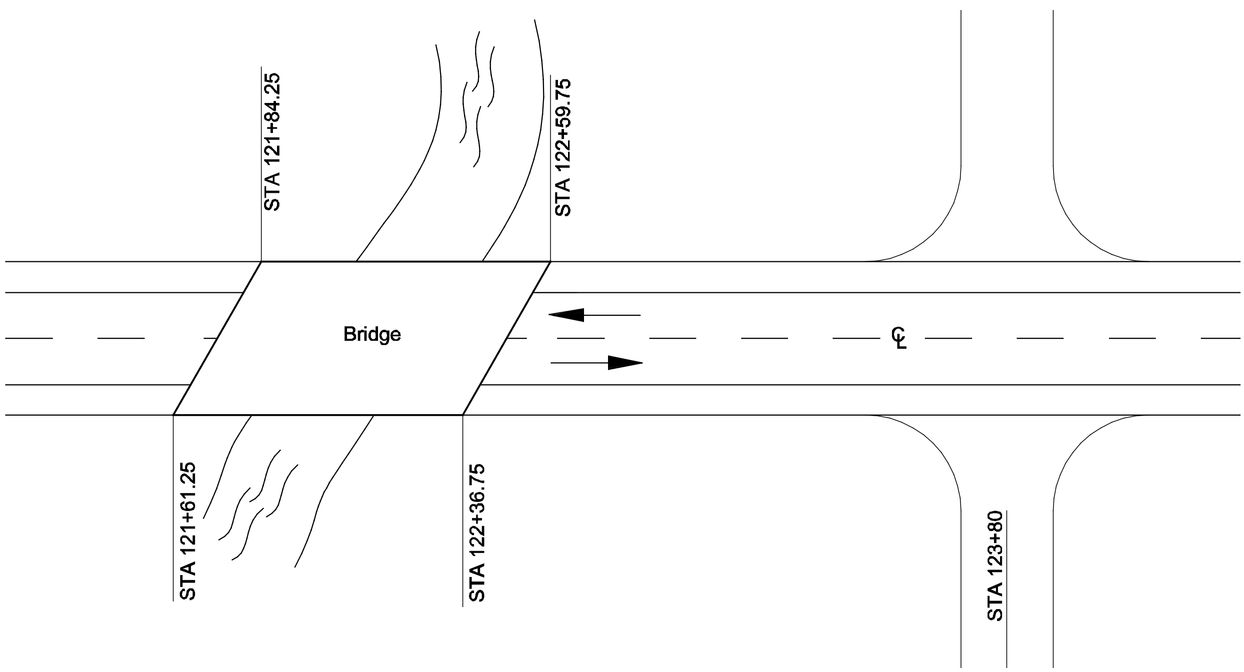
   [9+90.00] - 12.50′ (the portion of the OTS outside of the length of need)
   = 9+77.50 Beginning Station

   [9+77.50] + 437.50′ w-beam + (2 x 50′ OTS)
   = 15+15.00 Ending Station

Additional discussion: If the rail had been on the right side, providing the additional length on the advancement side of the adjacent traffic would be calculated from the end station of the length of need working back on stationing (15+12.50 back to 9+75.00).

Example 13-5: Computations of Pay Quantities for W-Beam Guardrail and Intersecting Roadway Terminal (IRT) Sections

Given: A bridge replacement project (on a two-way, two-lane highway) calls for guardrail lengths of need from the end of the bridge rail of 141.5 feet and 76.2 feet, for the approach and departure sides respectively. (See Example 9-3). The roadway width is 40 feet (12 foot lanes and 8 foot shoulders) and R/W is 80 feet from centerline on each side of the road. There are private approaches needed on each side of the roadway at station 123+80. The approaches are currently designed 24 feet wide with 25 foot radii per *MDT Detailed Drawings* and cannot be relocated beyond minor adjustments.



Problem: Determine appropriate w-beam guardrail treatment for the end of the bridge with the private approaches, and determine the station limits and quantities for the guardrail.

Solution:

1. Determine the appropriate treatment for the bridge approach rail connecting to the bridge rail on the right side:

   Calculate the available distance from the end of the bridge rail to the beginning of the approach radius.

   Approach station [123+80.00] – 12′ half approach width – 25′ radius = begin of radius station [123+43.00]

   Begin of radius station [123+43.00] – end of bridge rail station [122+36.75] = 106.25′ of available space.

Divide the departure length of need by the standard increment to determine the full strength guardrail needed.

76.2′ ÷ 12.5′/section = 6.096 sections, Round ⇒ 7 sections of rail for length of need

Since the last 12.5′ of a W-beam OTS is not full strength, add 12.5′ to the needed guardrail length.

(7 sections x 12.5′/section) + 12.5′ = 100.0′

100.0′ of needed guardrail < 106.25′ of space available, therefore use standard w-beam approach rail with a Bridge Approach Section and OTS.

The guardrail on the right side will be from station 122+36.75 to 123+36.75 and will include one 25-foot Bridge Approach Section (bid per each), one 50-foot OTS (bid per each), and 25 feet of w-beam.

2. Determine the appropriate treatment for the bridge approach rail connecting to the bridge rail on the left side:

Calculate the available distance from the end of the bridge rail to the beginning of the approach radius.

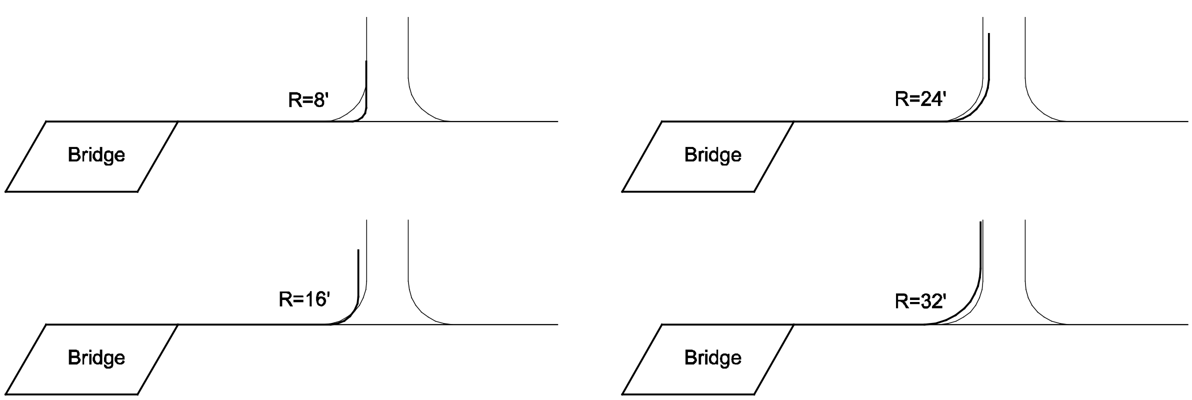
Begin of radius station [123+43.00] – end of bridge rail station [122+59.75] = 83.25′ available. This distance is long enough to allow the minimum length of blunt end protection with an OTS for the bridge end (25′ Bridge Approach Section and 50′ OTS). However, this option does not provide the calculated advancement length needed for shielding the crossing hazard.

Determine a bridge approach rail solution using an IRT:

The edge of the current approach station is [123+80.00] – 12′ half width of approach = [123+68.00]

The space for rail with an IRT = [123+68.00] - [122+59.75] = 108.25′

IRT radii are available in increments of 8 feet, up to 32 feet. Subtracting each radius from the space available leaves available lengths of tangent guardrail of 100.25′, 92.25′, 84.25′, and 76.25′. The closest fit configuration for each IRT radius option is shown below (approach end is at the R/W limit for all cases).



For this example, all options fit within the available R/W and could potentially be used with minor widening, narrowing, and/or relocation of the approach location. In this instance, the 24 foot radius was selected (with the approach being relocated 4 feet ahead on station), based on the anticipated traffic needs. Selecting this option does not require any additional width in guardrail widening in front of the rail or a reduction in approach radius. It also provides nearly 10 feet of space between the R/W line and the end of rail for maintenance/utility access.

Determine stationing:

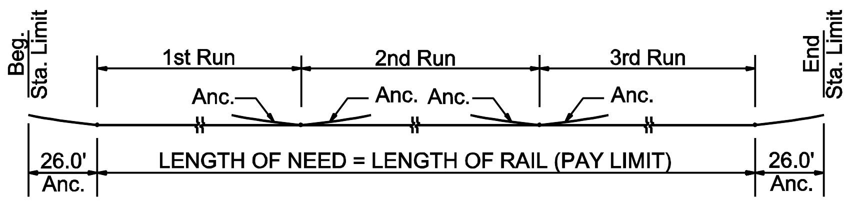
[122+59.75] + 25′ (bridge approach section) + 62.5′ (normal run w-beam) + 24′ (IRT radius) = [123+71.25]

The guardrail on the left side will be from station 122+59.75 to 123+71.25 and will include one 25-foot Bridge Approach Section (bid per each), 62.5 feet of normal run w-beam, and 62.5 feet of Intersecting Roadway Terminal.

Example 13-6: Cable Guardrail

Given: Low-tension cable guardrail is warranted between Station 20+00 and 75+00.

Problem: Determine the beginning and ending stations for the cable rail, the length of rail for payment, and the number of terminal sections needed and measured for payment.



Solution:

1. [75+00.00] – [20+00.00] = 5,500.0′ feet of cable rail measured for payment

2. 5,500.0′ ÷ 2000′ (maximum run length) = 2.75, Round ⇒ 3 runs of rail needed

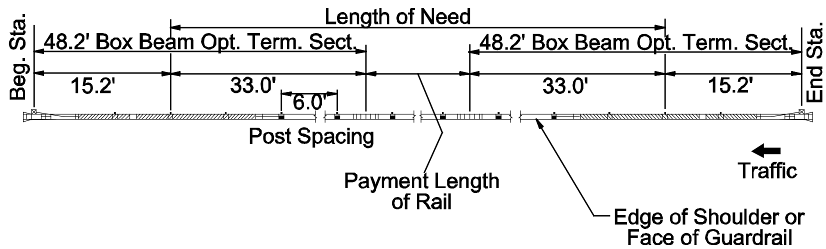
3. Two terminal sections are needed per run of rail:

   3 runs x 2 terminals/run = 6 terminal sections needed (bid per each)

4. [20+00.00] – 26′ terminal section length = 19+74.00 Beginning Station
   [75+00.00] + 26′ = 75+26.00 Ending Station

Example 13-7: Box Beam Guardrail

Given: Box Beam guardrail is warranted between Stations 17+50.00 and 32+75.00. The facility is a two-lane, two-way roadway requiring an Optional Terminal Section (OTS) at each end, and there is a private approach at station 33+40 on the same side of the roadway as the guardrail.



Problem: Determine the beginning and ending stations and the length of rail for payment.

Solution:

1. [([32+75.00] – [17+50.00]) - (2)(33.0′ of full strength rail per OTS)] ÷ 18′ increment = 81.06 sections, Round $\Rightarrow$ 82 sections of Box Beam guardrail

2. 82 x 18′ = 1,476.0′ Payment Length of Box Beam Guardrail

3. Because of the approach located at station 33+40, locate the rail as far back on stationing as possible to reduce impacts to sight distance and turning maneuvers associated with the approach.
   [32+75.00] + 15.2′ of OTS outside of length of need = 32+90.20 Ending Station
   [32+90.20] - 1476.0′of standard run rail - (2 x 48.2′ OTS length) = 17+17.80 Beginning Station

4. 2 Box Beam Optional Terminal Sections bid per each

Example 13-8: Finish Grade Control

Given: 4-lane freeway with 7 miles of construction
Interchange with construction of four 0.4 mile long ramps
2-lane intersecting roadway with 1 mile of construction

Pavement section:

0.30′ Plant Mix
1.20′ Crushed Aggregate Course
2.00′ Special Borrow

Problem: Determine the amount of finish grade control staking required for the project.

Solution: Calculate the course mile of finish grade control staking for the mainline, ramps and intersecting roadway (round up to nearest 50-foot increment):

2 x 7.0 mile = 2 x 36,960′, rounded to 2 x 37,000′ = subgrade for mainline	74,000 feet
2 x 7.0 mile = special borrow for mainline	74,000 feet
2 x 7.0 mile = crushed aggregate for mainline	74,000 feet
4 x 0.5 x 0.4 mile = 4 x 0.5 x 2,112′, rounded to 4 x 0.5 x 2,150′ = subgrade for ramps	4,300 feet
4 x 0.5 x 0.4 mile = special borrow for ramps	4,300 feet
4 x 0.5 x 0.4 mile = crushed aggregate for ramps	4,300 feet
1.0 mile = 5,280′, rounded to 5,300′ = subgrade for intersecting road	5,300 feet
1.0 mile = special borrow for intersecting road	5,300 feet
1.0 mile = crushed aggregate for intersecting road	5,300 feet
	250,800 feet total

APPROACH GRADING BACKGROUND

Approach grading will be paid the same as the mainline grading, (i.e. Unclassified Excavation or Embankment in Place), as further described in Chapter 13 - Quantity Summaries. Approach fills within the clear zone will be 10:1, regardless of fill height. This does not apply where the approach is shielded with guardrail. See the *MDT Detailed Drawings* for all approach grading information.

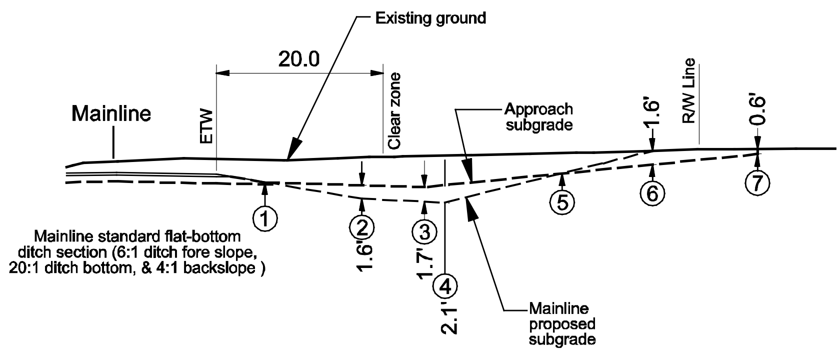
Earthwork quantities for approaches can be calculated using several appropriate methods, including three-dimensional (3D) modeling, not all of which are covered here. It is important to note that as the complexity, or importance of an approach increases, so should the level of design increase. For approaches with major realignment (e.g., button hook approaches), substantial changes in grade, or other unique design features, more detailed earthwork calculations may be necessary. It is recommended that the same method that was used to generate the mainline quantities be used on these approaches. Details including plan and profile should be provided for public approaches, as well as the private or farm field approaches requiring significant design work.

Two example methods for calculating approach grading quantities on approaches not requiring significant design work will be outlined in the following sections. The first method of calculation utilizes tabulated end areas and should cover the most common approaches being designed and will work for approaches in both cut or fill sections. The second method is only for very basic approaches with minimal grading impact to mainline grading, and where the approach grading is in a fill section compared to either existing ground or proposed mainline grading.

Example 13-9: Approach Grading – Method 1, Tabulated End Areas

1. **Procedure**.
   a. This procedure uses the mainline cross section that was taken at the centerline of the approach. Therefore, ensure that the approach is accurately drawn in the cross section. Method 1, as demonstrated, would not be appropriate for approaches with a severe skew.
   b. Steps “c” thru “f” follow the Approach Earthwork Example Calculation, shown below.
   c. Measure the horizontal distance from the intersection of the mainline surfacing inslope and the approach subgrade ① to each distinct grade break on the existing ground or proposed mainline subgrade line ②,③,④,⑥, & ⑦, and cut/fill transition points ⑤. This distance is entered as a “Station” in the Earthwork Computation Form (see table below). Only distinct/abrupt grade breaks that the design team believes affect the accuracy of earthwork quantity need to be measured.
   d. Measure the vertical distances at each point determined in Step “c”.
   e. Use the vertical distance to obtain an area from the Approach Grading Quantities tables, shown below. It is recommended that the design team interpolate the end area values from the actual vertical distances obtained in Step “d” (interpolated values used in the Approach Earthwork Example Calculation, shown below). The values provided are based on a standard approach with a 34-foot wide subgrade (see *MDT Detailed Drawings*).
   f. Complete the Earthwork Computation Form (see table below). Adjustments (shrink/swell factors) to the Excavation and Embankment quantities should be made when entering the quantities into the mainline grading. The adjusted values for the approach grading quantities obtained from the mainline grading should be the values entered in the plans (i.e., Additional Grading Summary Frame & Cross Section Sheets).

APPROACH EARTHWORK EXAMPLE CALCULATION

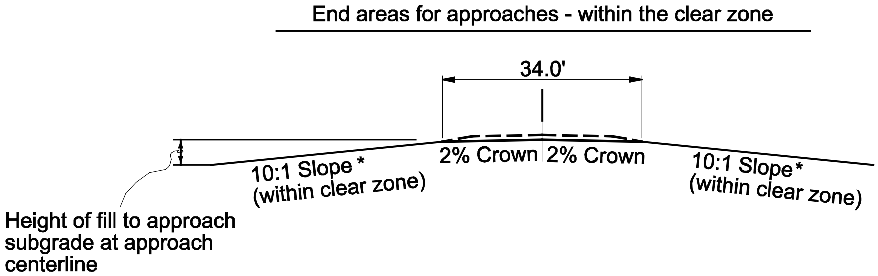


EARTHWORK COMPUTATION FORM

STATION	DIST. (ft)	AREAS IN SQUARE FEET				VOLUMES IN CUBIC YARDS					
		CUT		FILL		EXCAVATION			EMBANKMENT		
		AREA	DOUBLE AREA	AREA	DOUBLE AREA	ACTUAL	SWELL FACTOR	ADJ. EXC.	ACTUAL	SHRINK FACTOR	EMB. +
0+00.0		0		0							
	11.6		0		65.2	0			14		
0+11.6		0		65.2							
	7.5		0		125	0			17		
0+19.1		0		59.8							
	2.5		0		137.8	0			6		
0+21.6		0		78.0							
	14.1		0		78	0			20		
0+35.7		0		0							
	10.9		109.4		0	22			0		
0+46.6		109.4		0							
	12.5		132.8		0	31			0		
0+59.1		23.4		0							
					TOTAL	**53**		*	**57**		*

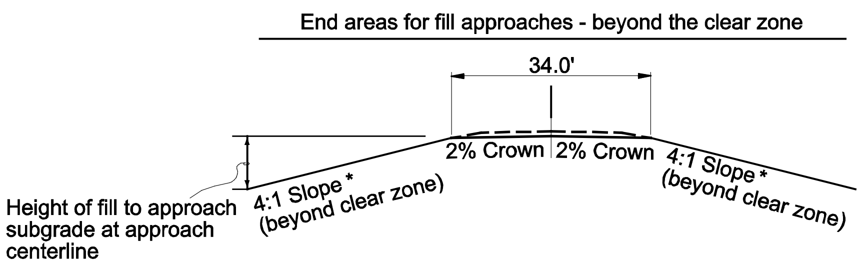
* VALUES SHOULD BE ADJUSTED AT THE SAME RATE AS MAINLINE. MAKE ADJUSTMENT WHEN ENTERING QUANTITIES INTO MAINLINE GRADING.

APPROACH GRADING QUANTITIES



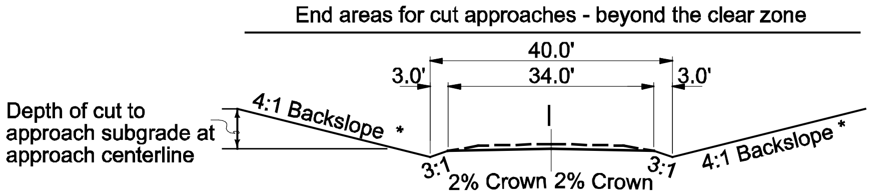
10:1 FILL SLOPE	
HEIGHT OF FILL (FT.)	AREA (SQ. FT.)
0.5	11
1	33
1.5	59
2	90
2.5	126
3	167
3.5	213
4	264
4.5	320
5	381

10:1 FILL SLOPE	
HEIGHT OF FILL (FT.)	AREA (SQ. FT.)
5.5	447
6	519
6.5	595
7	676
7.5	762
8	853
8.5	949
9	1050
9.5	1156
10	1267



4:1 FILL SLOPE	
HEIGHT OF FILL (FT.)	AREA (SQ. FT.)
0.5	11
1	30
1.5	51
2	73
2.5	98
3	125
3.5	153
4	184
4.5	216
5	251

4:1 FILL SLOPE	
HEIGHT OF FILL (FT.)	AREA (SQ. FT.)
5.5	288
6	326
6.5	367
7	410
7.5	454
8	501
8.5	550
9	600
9.5	653
10	707



4:1 BACKSLOPE	
DEPTH OF CUT (FT.)	AREA (SQ. FT.)
0.5	44
1	73
1.5	103
2	135
2.5	170
3	206
3.5	245
4	285
4.5	327
5	372

4:1 BACKSLOPE	
DEPTH OF CUT (FT.)	AREA (SQ. FT.)
5.5	324
6	359
6.5	394
7	430
7.5	467
8	505
8.5	544
9	585
9.5	626
10	668

Example 13-10: Approach Grading – Method 2, Basic Fill Approach Grading

1. **Procedure**.

   a. This procedure uses the mainline cross section that was taken at the centerline of the approach. Therefore, ensure that the approach is accurately drawn in the cross section. Method 2 is only appropriate for use on approaches with minimal grading impacts to mainline grading, and where the approach grading is in a fill section compared to either existing ground or proposed mainline grading.

   b. Steps "c" thru "f" follow the Basic Fill Approach Grading Example, shown below.

   c. Measure the fill area between the proposed slopes or existing ground (whichever is appropriate) and the approach subgrade.

   d. Multiply the measured area of fill by the width of the approach and then convert to cubic yards. This will estimate the volume of the central 24 feet of the approach.

      Example fill volume for central 24 feet of approach:

      (30.5 sq. ft. x 24.0 ft.)/(27 cu.ft./cu. yd) = 27.1 cu. yds.

   e. Estimate the approach fill slope volume by multiplying the height at the mainline ditch (fill catch) by the length of fill by the slope rate (4:1 = 4), then convert to cu.yds. Using this method will average both left and right of mainline at the same volume. Additionally, with this method it is not necessary to make a separate calculation for the 10:1 slopes inside of the clear zone.

      Example fill volume for approach slope grading (LT. & RT.):

      (1.5 ft. x 37.7 ft. x 4 ft./ft.)/(27 cu.ft./cu.yd.) = 8.4 cu. yds.

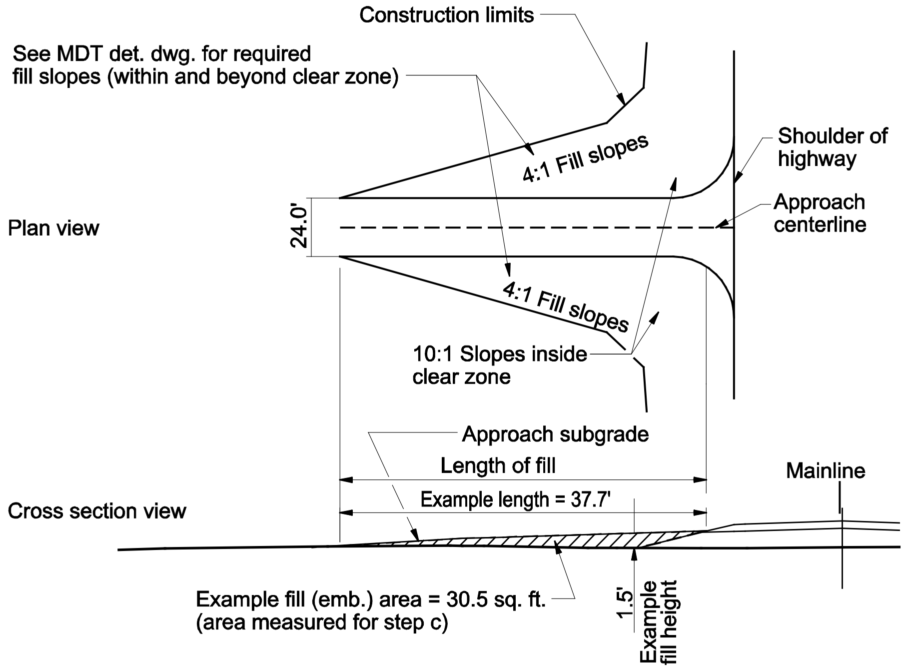
   f. Sum the estimated volumes from the approach's central 24 ft. (from Step "d") and the approach slope grading (from Step "e").

      Example total approach fill (EMB.) volume:

      27.1 cu.yds. + 8.4 cu.yds. = 35.5 cu.yds.

   g. If the grading pay item is Unclassified Excavation (UNCL. EX.), then adjust (shrink/swell) Embankment (EMB+) quantities in the same manner as done for the mainline. Make the adjustment when entering quantities into the mainline grading. The adjusted values for the approach grading quantities obtained from the mainline grading should be the values entered in the plans (i.e., Additional Grading Summary Frame & Cross Section Sheets).

BASIC FILL APPROACH GRADING EXAMPLE



Example 13-11: Topsoil Replacement Quantities

Given: A rural reconstruction project, utilizing unclassified excavation with 20% shrink and with the following topsoil and seeding quantities:

TOPSOIL & SEEDING											
STATION		cubic yards	acres							square yards	REMARKS
		TOPSOIL SALVAGING & PLACING	SEED			FERTILIZER		CONDITION SEEDBED	MULCH	EROSION CONTROL BLANKET (LONG-TERM)	
FROM	TO		NO. 1	NO. 2	NO.3	NO. 1	NO. 2				
53+81.86	83+00.00	1,450	4.4	2.0	0.2	4.4	2.0	4.6	2.0		
83+00.00	113+00.00	2,348	0.2	6.2	2.1	0.2	6.2	2.3	6.2		
93+52.02	94+01.48									106	BRIDGE END GRADING EROSION CONTROL
113+00.00	143+00.00	721	0.3		1.0	0.3		1.3			
143+00.00	170+19.65	767	5.2		1.5	5.2		6.7			INCLUDES CONNECTION TO PTW
TOTAL		5,286	10.1	8.2	4.8	10.1	8.2	14.9	8.2	106	

Problem: Determine the topsoil replacement quantities.

Solution: Topsoil replacement is a grading quantity that is needed to adjust the earthwork on a project to account for the topsoil that is salvaged from the roadway construction limits prior to the general grading operation. This material was in place when the project was surveyed and the digital terrain model (DTM) was created, and is included in the line representing the existing ground to which cut and fill quantities are measured. The removal of this material prior to grading has the effect of lowering the existing ground line wherever it is removed, thereby underestimating the amount of embankment needed in fill sections, and overestimating the amount of material generated from cut sections. For either condition, embankment material must be added to the earthwork run to account for the topsoil that is removed.

To estimate the amount of embankment required for topsoil replacement, the quantity of topsoil salvaged needs to be adjusted by the project shrink factor. The Standard Specifications require that the contractor salvage enough topsoil from within the construction limits to dress the finished slopes with four inches of topsoil. For this reason, the depth, quality and distribution of the topsoil on the existing slopes is somewhat irrelevant. Similarly, areas where topsoil is not removed (e.g. Foundation Treatment areas) do not typically need special consideration when calculating Topsoil Salvaging and Placing quantities. The Topsoil Salvaging and Placing quantities have already been calculated for this example and are indicated in the summary frame above. Although the Summary is Topsoil & Seeding, the quantity splits are intended to aid in calculating topsoil replacement grading quantities, and to show the distribution of these quantities more uniformly in the mass diagram and earthwork run.

Since grading on this project is measured as Unclassified Excavation, an earthwork run and mass diagram are developed. The unadjusted quantities of topsoil salvage should be entered into the earthwork run as point additional embankment quantities for each section, and adjusted according to the project shrink factor. It isn't critical whether the "from" or "to" station is used to identify the locations where these quantities are added in the earthwork run, only that the method used is consistent for the project.

ADDITIONAL GRADING					
STATION		cubic yards			REMARKS
		INCL. IN ROADWAY		ADD. UNCL. EXC.	
FROM	TO	UNCL. EXC.	EMB.+		
53+81.86	83+00.00		1,740		TOPSOIL REPLACEMENT
60+91.00		15	230		FARM FIELD APP. RT.
61+78.00	64+63.90	*	*		MAILBOX TURNOUT LT.
63+08.00		25	5		PRIVATE APP. LT.
69+26.00	72+12.00	*	*		MAILBOX TURNOUT RT.
70+83.00		30	80		PRIVATE APP. RT.
78+77.00		15	70		PRIVATE APP. LT.
81+11.44	81+87.56		5		G-RAIL OTS EMB. WIDENING RT.
82+60.65	83+36.77		25		G-RAIL OTS EMB. WIDENING LT.
83+00.00	113+00.00		2,818		TOPSOIL REPLACEMENT
93+25.02	93+50.02		65		G-RAIL BRIDGE APPROACH SECTION WIDENING LT.
93+25.02	93+50.02		10		G-RAIL BRIDGE APPROACH SECTION WIDENING RT.
93+52.02	94+01.48	930	10		BRIDGE END GRADING - SEE DETAIL
94+03.48	94+28.48		25		G-RAIL BRIDGE APPROACH SECTION WIDENING LT.
94+03.48	94+28.48		50		G-RAIL BRIDGE APPROACH SECTION WIDENING RT.
93+87.00		15			DRAINAGE DITCH - SEE BRIDGE END GRADING DETAIL
96+15.98	96+92.10		5		G-RAIL OTS EMB. WIDENING LT.
99+27.00		50	5		PRIVATE APP. LT. - 48' WIDE
101+40.98	102+06.85		45		G-RAIL OTS EMB. WIDENING RT.
102+35.00		80	520		PRIVATE APP. RT.
107+00.00		170			PRIVATE APP. LT.
113+00.00	143+00.00		865		TOPSOIL REPLACEMENT
119+98.88	120+75.00		5		G-RAIL OTS EMB. WIDENING LT.
142+47.25	143+07.74		45		G-RAIL OTS EMB. WIDENING RT.
143+00.00	170+19.65		920		TOPSOIL REPLACEMENT
143+25.00		225	15		FARM FIELD APP. RT. - 12' WIDE
147+95.00		300			FARM FIELD APP. RT. - 12' WIDE
150+75.00	151+51.12		5		G-RAIL OTS EMB. WIDENING LT.
153+30.00		10	2,610		PRIVATE APP. LT. (MT DNRC)
155+79.50	156+55.62		5		G-RAIL OTS EMB. WIDENING RT.
163+66.00	166+50.00	*	*		MAILBOX TURNOUT LT.
SUBTOTAL		~	~	~	

Note: # EXCAVATION QUANTITIES-MATERIAL UNSUITABLE FOR ROADWAY EMBANKMENTS

* INCLUDED IN MAINLINE GRADING

Additional discussion: For projects measuring grading as Embankment-in-Place, the entire quantity of topsoil salvaged is identified on a separate line of the Grading Frame, and identified as "TOPSOIL REPLACEMENT" in the Remarks column. For these projects, no adjustments to grading are made, and additional grading items are not included in the earthwork run.