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CHAPTER FORTY-THREE

HORIZONTAL ALIGNMENT

43-1.0 DEFINITIONS

This Section presents definitions for basic elements of horizontal alignment. Section 43-6.0 presents mathematical details for horizontal curves (e.g., deflection angle, point of curvature).

1. Simple Curves. These are continuous arcs of constant radius which achieve the necessary highway deflection without an entering or exiting transition.

2. Compound Curves. These are a series of two or more simple curves with deflections in the same direction immediately adjacent to each other.

3. Reverse Curves. These are two simple curves with deflections in opposite directions which are joined by a relatively short tangent distance.

4. Broken-Back Curves. These are closely spaced horizontal curves with deflection angles in the same direction with an intervening, short tangent section.

5. Superelevation. Superelevation is the amount of cross slope or "banking" provided on a horizontal curve to help counterbalance the centrifugal force of a vehicle traversing the curve.

6. Maximum Superelevation (e_{max}). The maximum rate of superelevation (e_{max}) is an overall superelevation control used on a specific facility. Its selection depends on several factors including climatic conditions, terrain conditions, type of area (rural or urban) and highway functional classification.

7. Superelevation Transition Length. The superelevation transition length is the distance required to transition the roadway from a normal crown section to full superelevation. Superelevation transition length is the sum of the tangent runout (TR) and superelevation runoff (L) distances:

    a. Tangent Runout (TR). Tangent runout is the distance needed to change from a normal crown section to a point where the adverse cross slope of the outside lane or lanes is removed (i.e., the outside lane(s) is level).

b. Superelevation Runoff (L). Superelevation runoff is the distance needed to change the cross slope from the end of the tangent runout (adverse cross slope removed) to a section that is sloped at the design superelevation rate.

8. Axis of Rotation. The superelevation axis of rotation is the line about which the pavement is revolved to superelevate the roadway. This line will maintain the normal highway profile throughout the curve.

9. Superelevation Rollover. Superelevation rollover is the algebraic difference (A) between the superelevated travel lane slope and shoulder slope on the outside of a horizontal curve.

10. Normal Crown (NC). The typical cross section on a tangent section (i.e., no superelevation).

11. Remove Adverse Crown (RC). A superelevated roadway section which is sloped across the entire traveled way in the same direction and at a rate equal to the cross slope on a tangent section.

12. Relative Longitudinal Slope. In superelevation transition sections on two-lane facilities, the relative gradient between the profile grade and edge of traveled way.

43-2.0 HORIZONTAL CURVES

43-2.01 General Theory

Horizontal curves are, in effect, transitions between two tangents. These deflectional changes are necessary in virtually all highway alignments to avoid impacts on a variety of field conditions (e.g., right-of-way, natural features, man-made features). The following presents a brief overview of the general theory of horizontal alignment. The designer should reference the AASHTO *A Policy on Geometric Design of Highways and Streets* for more information.

43-2.01(01) Basic Curve Equation

The point-mass formula is used to define vehicular operation around a curve. Where the curve is expressed using its radius, the basic equation for a simple curve is:

$$R = \frac{V^2}{15(e + f)}$$

Where:

R	=	radius of curve, ft
e	=	superelevation rate
f	=	side-friction factor
V	=	vehicular speed, mph

43-2.01(02) Theoretical Approaches

Establishing horizontal curvature criteria requires a determination of the theoretical basis for the various factors in the basic curvature equation. These include the side-friction factor (f) and the distribution method between side friction and superelevation. The theoretical basis will be one of the following:

1. Open-Roadway Conditions. The theoretical basis for horizontal curvature assuming open-roadway conditions includes:

   a. relatively low side-friction factors (i.e., a relatively small level of driver discomfort); and

   b. the use of AASHTO Method 5 to distribute side friction and superelevation.

   Open-roadway conditions apply to all rural facilities and all urban facilities where the design speed (V) >45 mph.

2. Low-Speed Urban Streets. The theoretical basis for horizontal curvature assuming low-speed urban street conditions includes:

   a. relatively high side-friction factors to reflect a higher level of driver acceptance of discomfort; and

   b. the use of AASHTO Method 2 to distribute side friction and superelevation.

   Low-speed urban streets are defined as streets within an urban or urbanized area where the design speed (V) $\leq$ 45 mph.

3. Turning Roadway Conditions. The theoretical basis for horizontal curvature assuming turning roadway conditions includes:

a. higher side-friction factors (than open-roadway conditions) to reflect a higher level of driver acceptance of discomfort; and

b. a range of acceptable superelevation rates for combinations of curve radius and design speeds to reflect the need for flexibility to meet field conditions for turning roadways.

Turning roadway conditions apply to turning roadways at intersections at-grade. See Chapter Forty-six.

43-2.01(03) Superelevation

Superelevation allows a driver to negotiate a curve at a higher speed than would otherwise be comfortable. Superelevation and side friction work together to offset the outward pull of the vehicle as it traverses the horizontal curve. In highway design, it is necessary to establish limiting values of superelevation (e_{max}) based on the operational characteristics of the facility. Values of e_{max} used by INDOT are discussed in Section 43-3.0.

43-2.01(04) Side Friction

AASHTO has established limiting side-friction factors (f) for various design speeds and various highway operating conditions. It is important to note that the f values used in design represent a threshold of driver discomfort <u>not</u> the point of impending skid. Different sets of f values have been established for different operating conditions (i.e., open roadway, low-speed urban street and turning roadway). The basis for the distinction is that drivers, through conditioning, will accept different levels of discomfort on different facilities.

<u>43-2.02 Selection of Horizontal Curve Type</u>

Because of their simplicity and ease of design, survey and construction, INDOT almost always uses the simple curve on the highway mainline. In rare instances, a simple curve may not be consistent with field conditions, and the designer may need to consider an alternative arrangement (e.g., a compound curve). Spiral curves will not be used.

43-2.03 <u>Minimum Radii</u>

The following tables present the minimum radii (R_{min}) for open-roadway facilities and low-speed urban streets; criteria for turning roadways are presented in Chapter Forty-six. To define R_{min}, a maximum superelevation rate (e_{max}) must be selected. These are as follows:

1. Figure 43-2A is applicable for facilities where e_{max} = 8% and open-roadway conditions apply.

2. Figure 43-2B is applicable to low-speed urban street conditions where e_{max} = 4% and e_{max} = 6% are applied.

See Section 43-3.0 for the selection of e_{max} for various facilities.

43-2.04 Maximum Deflection Without Curve

It may be appropriate to design a facility without a horizontal curve where small deflection angles are present. As a guide, the designer may retain deflection angles of about 1º or less (urban) and 0.5º or less (rural) for the highway mainline. The absence of a horizontal curve will not likely affect driver response or aesthetics.

43-2.05 Minimum Length of Curve

Short horizontal curves may provide the driver the appearance of a kink in the alignment. To improve the aesthetics of the highway, the designer should lengthen short curves, if practical, even if not necessary for engineering reasons. The following guidance should be used to compare the calculated curve length to the recommended minimum length:

1. General. The minimum length of curve on open roadways should be based on the deflection angle (Δ) as follows:

   a. $\Delta \leq 1^{\circ}$ 100 ft,
   b. $1^{\circ} < \Delta \leq 2^{\circ}$ 200 ft,
   c. $2^{\circ} < \Delta \leq 3^{\circ}$ 300 ft,
   d. $3^{\circ} < \Delta \leq 4^{\circ}$ 400 ft,
   e. $4^{\circ} < \Delta \leq 5^{\circ}$ 500 ft, and
   f. $\Delta > 5^{\circ}$ use calculated length.

   The minimum length of curves on low-speed urban streets will be determined on a case-by-case basis.

2. All Freeways and Rural Highways. The minimum length of curve in feet should desirably be 15V for aesthetics. V equals the design speed in mph.

43-2.06 Shoulder Treatment

On facilities with relatively sharp horizontal curves as indicated in the Chapter III Table, calculated and design values for traveled way widening on open highway curves (two-lane highways, one-way, or two-way), in the AASHTO *A Policy on Geometric Design of Highways and Streets* and high truck volumes (> 1000 AADT), a full-structural strength shoulder should be provided on both sides of a sharp horizontal curve in lieu of pavement widening. The following will apply:

1. Strengthened Length. The strengthened shoulder should be available from the beginning of the superelevation transition before the curve to the end of the transition beyond the curve.

2. Bituminous Traveled Way. The pavement structure of the strengthened shoulder will match that of the traveled way.

3. Concrete Traveled Way/Bituminous Shoulder. The INDOT Pavement Design Committee will determine the pavement structure of the strengthened shoulder.

4. Concrete Traveled Way/Concrete Shoulder. The pavement structure of the strengthened shoulder will match that of the traveled way.

See Chapter III of the AASHTO *A Policy on Geometric Design of Highways and Streets* for more information on pavement widening.

43-3.0 SUPERELEVATION

43-3.01 Superelevation Rates (Open-Roadway Conditions)

43-3.01(01) General

Open-roadway conditions are typically used on all rural highways and on all urban facilities where V > 45 mph. These types of facilities generally exhibit relatively uniform traffic operations. Therefore, for superelevation development, the flexibility normally exists to design

horizontal curves with the more conservative AASHTO Method 5 (for distribution of superelevation and side friction). The following sections present the specific design criteria for superelevation rates assuming open-roadway conditions.

43-3.01(02) Maximum Superelevation Rate

The selection of a maximum rate of superelevation (e_{max}) depends upon several factors. These include urban/rural location and prevalent climatic conditions within Indiana. For open-roadway conditions, INDOT has adopted the following for the selection of e_{max}:

1. Rural Facilities. An e_{max} = 8% is typically used on all rural roadways. Exceptions should be evaluated on a case-by-case basis.

2. Urban Facilities (V > 45 mph). An e_{max} = 8% is typically used on all urban facilities where the design speed (V) is greater than 45 mph. Other rates of superelevation, e_{max} = 6% or e_{max} = 4% may be used where the design speed is equal to or less than 45 mph or where site specific conditions warrant.

43-3.01(03) Superelevation Rates

Based on the selection of e_{max} = 8% or 6% or 4% and the use of AASHTO Method 5 to distribute e and f, Figure 43-3A, 43-3A1, 43-3A2, 43-3A3, 43-3A4 or 43-3A5 allow the designer to select the superelevation rate for any combination of curve radii (R) and design speed (V). Normally, the design speed selected for determining the superelevation rate will be the same as that used for the overall project design. However, site-specific factors may indicate a need to use a higher design speed specifically to determine the superelevation rate. This may be appropriate if the designer anticipates that travel speeds higher than the project design speed will occur at the horizontal curve with some frequency. Examples include:

1. Transition Areas. Where a highway is transitioning from a predominantly rural environment to an urban environment, travel speeds in the transition area within the urban environment may be higher than the urban design speed.

2. Downgrades. Where a horizontal curve is located at the bottom of a downgrade, travel speeds at the curve may be higher than the overall project design speed. As suggested adjustments, the design speed used for the horizontal curve may be 5 mph (3% - 5% downgrades) or 10 mph (>5% downgrades) higher than the project design speed. This adjustment may be more appropriate for divided facilities than for 2-lane, 2-way highways.

3. Long Tangent. Where a horizontal curve is located at the end of a long tangent section, a higher design speed (up to 10 mph higher) than the project design speed may be appropriate.

43-3.01(04) Minimum Radii Without Superelevation

A horizontal curve with a very large radius does not require superelevation, and the normal crown section (NC) used on tangent sections can be maintained throughout the curve. On sharper curves for the same design speed, a point is reached where a superelevation rate of .020 across the total traveled way width is appropriate. Figure 43-3B provides the threshold (or minimum) radius for a normal crown section at various design speeds. The figure also presents the curve radii ranges where "remove (adverse) crown" (RC) applies. This table applies to all highways where open-roadway conditions are used.

43-3.02 Superelevation Rates (Low-Speed Urban Streets)

43-3.02(01) General

In built-up areas, the combination of wide pavements, proximity of adjacent development, control of cross slope and profile for drainage, frequency of cross streets, and other urban features make superelevation impractical and undesirable. Usually, superelevation is not provided on local streets in residential areas. It may be considered on local streets in industrial areas to facilitate operation. If superelevation is used, curves should be generally designed for a maximum superelevation rate of 4%. If terrain dictates sharp curvature, a maximum superelevation rate of 6% is justified if the curve is long enough to provide an adequate superelevation transition.

Low-speed urban street conditions may be used for superelevating streets in urban and urbanized areas where V<45 mph. A superelevation rate of 6% is considered the maximum desirable rate for low-speed urban street design. On these facilities, providing superelevation at horizontal curves is frequently impractical because of roadside conditions and, in some cases, may result in undesirable operational conditions. The following lists some of the characteristics of low-speed urban streets which often complicate superelevation development:

1. Roadside Development/Intersections/Driveways. Built-up roadside development is commonly adjacent to low-speed urban streets. Matching superelevated curves with many driveways, intersections, sidewalks, etc., creates considerable complications. This may also require re-shaping parking lots, lawns, etc., to compensate for the higher elevation of the high side of the superelevated curve.

2. Non-Uniform Travel Speeds. On low-speed urban streets, travel speeds are often non-uniform because of frequent signalization, stop signs, vehicular conflicts, etc. It is undesirable for traffic to stop on a superelevated curve, especially when snow or ice is present.

3. Limited Right-of-Way. Superelevating curves often results in more right-of-way impacts than would otherwise be necessary. Right-of-way is often restricted along low-speed urban streets.

4. Wide Pavement Areas. Many low-speed urban streets have wide pavement areas because of high traffic volumes in built-up areas, the absence of a median and the presence of parking lanes. In general, the wider the pavement area, the more complicated will be the development of superelevation.

5. Surface Drainage. Proper pavement drainage on low-speed urban streets can be difficult even on sections with a normal crown. Superelevation introduces another complicating factor.

As discussed in Section 43-2.0, AASHTO Method 2 is used to distribute superelevation and side friction in determining superelevation rates for the design of horizontal curves on low-speed urban streets. In addition, relatively high side-friction factors are used. The practical impact is that superelevation is rarely warranted on these facilities.

The higher side-friction factors for low-speed urban streets are consistent with driver acceptance of more discomfort in urban areas.

43-3.02(02) Superelevation Rates

Figure 43-3C is used to determine the superelevation rate for horizontal curves of given radius on a low-speed urban street of given design speed. The figure is divided into three areas. The following examples illustrate how to use Figure 43-3C for site conditions within each area.

* * * * * * * * *

Example 43-3.1

Given: Design speed = 35 mph
Radius = 650 ft
Cross slope (on tangent) = 2%

Problem: Determine the superelevation rate.

Solution: From Figure 43-3C the required superelevation rate = -.039. Therefore, a normal crown section may be maintained throughout the curve (i.e., e = -.020).

Example 43-3.2

Given: Design speed = 35 mph
Radius = 500 ft

Problem: Determine the superelevation rate.

Solution: From Figure 43-3C, the required superelevation rate = +.009. This falls in the area where the roadway should be uniformally superelevated at the cross slope of the roadway on tangent (typically .020). This is the desirable treatment. However, it is acceptable to superelevate the roadway at the theoretical superelevation rate (+.009), if this is consistent with field conditions (e.g., surface drainage will work properly).

Example 43-3.3

Given: Design speed = 35 mph
Radius = 500 ft

Problem: Determine the superelevation rate.

Solution: Figure 43-3C yields a required superelevation rate = +.03. Therefore, the entire pavement should be transitioned to this rate.

* * * * * * * * *

43-3.02(03) Minimum Radius Without Superelevation

On a low-speed urban street, a horizontal curve with a sufficiently large radius does not require superelevation; therefore, the normal crown section can be maintained around a curve. The threshold exists where the theoretical superelevation equals -.02. The lower boundary of the shaded area in Figure 43-3C illustrates this threshold. For convenience, see Figure 43-3D, Curve Radius for Normal-Crown Section and Remove (Adverse)-Crown Section (Low-Speed Urban Street).

43-3.03 Transition Length (Open-Roadway Condition)

As defined in Section 43-1.0, the superelevation transition length is the distance required to transition the roadway from a normal crown section to the full design superelevation (as determined from the figures based on the selected e_{max}). The superelevation transition length is the sum of the tangent runout distance, *TR*, and superelevation runoff length, *L*.

43-3.03(01) Two-Lane Roadway

1. Superelevation Runoff. Figure 43-3A and 43-3A1, show the superelevation runoff length, L_2, for various combinations of curve radius and design speed. The length is calculated as follows:

$$L_2 = We(RS) \qquad \text{(Equation 43-3.1)}$$

Where:

L_2 = Superelevation runoff length (assuming the axis of rotation is about the roadway centerline), ft

W = Width of rotation (assumed to be 12 ft)

e = Superelevation rate

RS = Reciprocal of relative longitudinal slope between the profile grade and outside edge of roadway (see Figure 43-3E)

The superelevation runoff length applies to the following:

a. a 2-lane, 2-way roadway rotated about its centerline; or

b. either directional roadway of a 4-lane divided facility, rotated about its centerline independently of the other roadway [see Section 43-3.03(02)].

2. Tangent Runout. The tangent runout distance is calculated as follows:

$$TR = \frac{L_2 S_{normal}}{e} \qquad \text{(Equation 43-3.2)}$$

Where:

TR = Tangent runout distance, ft

L_2 = Superelevation runoff length, ft (Equation 43-3.1)

S_{normal} = Travel lane cross slope on tangent (typically .02)

e = Design superelevation rate (i.e., full superelevation for horizontal curve)

This will ensure that the relative longitudinal gradient of the tangent runout equals that of the superelevation runoff.

43-3.03(02) Multilane Highway

1. Superelevation Runoff. The superelevation runoff distance is calculated as follows:

$$L = \frac{wn_1eb_w}{G} \qquad \text{(Equation 43-3.3)}$$

Where:

L = Superelevation runoff length, ft; rounded up to the next 15-ft increment

w = Width of one traffic lane, ft

n_1 = Number of lanes rotated

e = Design superelevation rate, %

b_w = Adjustment factor for number of lanes rotated (see Figure 43-3G)

G = Maximum relative gradient, %

2. Tangent Runout. The tangent runout distance is calculated from Equation 43-3.2, same as for a two-lane roadway.

The length of tangent runout is determined by the amount of adverse cross slope to be removed and the rate at which it is removed. To effect a smooth edge of pavement profile, the rate of removal should equal the relative gradient used to define the superelevation runoff length.

Since the cross slope on a multilane highway may not be constant across all lanes. If there are three lanes in the same direction, the first two lanes will be at 2% and the third will be at 3%. See Section 45-1.01(02) Item 2b.

This will ensure that the relative longitudinal gradient of the tangent runout equals that of the superelevation runoff.

43-3.03(03) Application of Transition Length

Once the superelevation runoff and tangent runout superelevation transition length have been calculated, the designer must determine how to fit the length in the horizontal and vertical planes. The following will apply:

1. Simple Curves. Typically, 75% of the superelevation runoff length will be placed on the tangent and the remainder on the curve. Exceptions to this practice may be necessary to meet field conditions. In extreme cases, the superelevation runoff may be distributed 50% - 70% on the tangent and 50% - 30% on the curve. It is acceptable to use Figure 43-3F to determine the percent of superelevation runoff to place on the tangent before the PC.

2. Reverse Curves. See Section 43-3.07 for a discussion on superelevation development for reverse curves.

3. Vertical Profile. At the beginning and ending of the superelevation transition, angular breaks would occur in the profile if not smoothed. These abrupt angular breaks should be smoothed by the insertion of short vertical curves at the two angle points. As a guide, the transitions should have a length of 60 ft.

4. Ultimate Development. If the facility is planned for ultimate development to an expanded facility, the designer should, where practical, reflect this in the initial superelevation transition application. For example, a four-lane divided facility may be planned for an ultimate six-lane divided facility. Therefore, the superelevation runoff length for the initial four-lane facility should be consistent with the future requirements of the six-lane facility. See Section 43-3.05.

43-3.03(04) Typical Figures

Figures 43-3H, 43-3I, 43-3J and 43-3K present typical figures for superelevation development. The following describes each figure.

1. Two-Lane Roadways. Figure 43-3H illustrates the superelevation development for a 2-lane roadway. The axis of rotation is about the centerline of the roadway.

2. Four-Lane Divided/No Future Third Lane. Figure 43-3 I illustrates the superelevation development for this case. The axes of rotation are about the two median edges.

3. Six-Lane Divided/Four-Lane Divided with Future Third Lane. Figure 43-3J illustrates the superelevation development for this case. The axes of rotation are about the two median edges or, where the future third lane is anticipated in the median, about the two future median edges. Also note that the figure illustrates how to treat the travel lane with a steeper cross slope (i.e., 3%).

4. Concrete Median Barrier. Figure 43-3K illustrates the superelevation development for a divided highway with a concrete median barrier (CMB). The axes of rotation are about the two edges of the CMB, which allows the barrier to remain within a horizontal plane throughout the horizontal curve. Also note that the figure illustrates how to treat the two inside shoulders in the superelevation development.

The designer should realize that these figures present acceptable methods for superelevation development which will often be applicable to typical site conditions. Other superelevation methods or strategies may need to be developed on a case-by-case basis to meet specific field conditions. For example, several highway features may significantly influence superelevation development for multilane divided highways. These include guardrail, median barriers, drainage and other field conditions. The designer should carefully consider the intended function of these features and ensure that the superelevated section and selected axis of rotation does not compromise their operation. The acceptability of superelevation development methods other than those in the typical figures will be judged individually.

For multilane facilities, the typical figures present the superelevation development for the inside and outside roadways separately. The coordination between the two roadways for a given station number will be determined individually. The selected design should, however, meet the following objective: The superelevation development for each roadway should begin such that full superelevation for each roadway is reached simultaneously (i.e., at the same station).

43-3.04 Transition Length (Low-Speed Urban Streets)

Low-speed urban streets are those urban facilities where $V \leq 45$ mph. If open-roadway conditions are used to determine the superelevation rate, then the superelevation transition length should be determined by the criteria for open-roadway conditions (Section 43-3.03). If the superelevation rate is determined by low-speed urban street conditions, then the superelevation transition length may be determined by the criteria that follow.

43-3.04(01) Two-Lane Roadways

Superelevation Runoff

Figure 43-3L presents the minimum superelevation runoff lengths (L_2) for 2-lane roadways. With the use of a straight-line interpolation for intermediate superelevation rates, the superelevation runoff may be calculated for any design speed and superelevation rate.

Tangent Runout

The tangent runout distance can be calculated from Equation 43-3.2, using L_2 from Figure 43-3L. This will ensure that the relative longitudinal gradient of the tangent runout equals that of the superelevation runoff.

43-3.04(02) Multilane Highways

Section 43-3.03 presents criteria for superelevation transition lengths for multilane highways assuming open-roadway conditions. This is accomplished by providing an adjustment factor "C" to apply to the transition length for a 2-lane, 2-way roadway (L_2). The procedures and formulas in Section 43-3.03 also apply to multilane highways assuming low-speed urban street conditions, except that L_2, the superelevation runoff length for 2-lane roadways, will be based on Figure 43-3L.

43-3.04(03) Application of Transition Length

The criteria presented in Section 43-3.03 for open-roadway conditions also apply to low-speed urban streets.

43-3.05 Axis of Rotation

The following discusses the axis of rotation for 2-lane, 2-way highways and multilane highways. Section 43-3.03 presents typical figures illustrating the application of the axis of rotation in superelevation development.

43-3.05(01) Two-Lane, Two-Way Highways

The axis of rotation will typically be about the centerline of the roadway on 2-lane, 2-way highways. This method will yield the least amount of elevation differential between the pavement edges and their normal profiles. It is acceptable to rotate about the inside or outside edge of the travelway. This may be necessary to meet field conditions (e.g., drainage on a curbed facility, roadside development).

On a 2-lane highway with an auxiliary lane (e.g., a climbing lane), the axis of rotation will typically be about the centerline of the two through lanes.

43-3.05(02) Multilane Divided Highways

If no future travel lane is planned, the axes of rotation will typically be about the two median edges for the multilane facility. Where these are used as the axes, the median will remain in a horizontal plane throughout the curve. Depending upon field conditions, the axes of rotation may be about the centerlines of the two roadways. Unless the two roadways are on independent alignment, this method results in different elevations at the median edges and, therefore, a compensating slope is necessary across the median. On narrow medians, the axis of rotation may be about the centerline of the entire roadway cross section.

The typical figures in Section 43-3.03 illustrate the axis of rotation for multilane facilities.

43-3.06 Shoulder Superelevation

43-3.06(01) High Side Shoulder

On the high side of superelevated sections, the following criteria will apply to the shoulder slope:

1. Typical Application. The high-side shoulder will be sloped as follows:

    a. If the superelevation rate on the curve is 4% or less, typically use 4% (its normal cross slope).

    b. If the superelevation rate on the curve is greater than 4% but less than or equal to 6%, typically use 2% down away from the traveled way.

    c. If the superelevation rate on the curve is greater than 6%, typically use 1% towards the traveled way.

d. Where the paved median shoulder is the high-side shoulder and is 4 ft or narrower, it should be sloped in the same plane as the travelway. See Figure 43-3M, Paved-Shoulder Cross Slopes, Superelevated Section, With Underdrains; or Figure 43-3N, Paved-Shoulder Cross Slopes, Superelevated Section, Without Underdrains, for more-specific information.

2. Maximum Rollover. Where the typical application cannot be provided, the high-side shoulder must be sloped such that the algebraic difference between the shoulder and adjacent travel lane will not exceed 8%.

3. Shoulder as Deceleration Lane. At some intersections, drivers may use a paved shoulder as a right-turn lane on a superelevated horizontal curve. Chapter Forty-six presents cross slope breakover criteria between a turning roadway and a through travel lane at an intersection at-grade. Where the shoulder is used by turning vehicles, the designer should limit the shoulder rollover to the turning roadway breakover criteria (4% to 5%).

43-3.06(02) Low Side (Inside) Shoulder

On the low side of a superelevated section, typical practice is to retain the normal shoulder slope until the adjacent superelevated travel lane reaches that slope. The shoulder is then superelevated concurrently with the travel lane until the design superelevation is reached (i.e., the inside shoulder and travel lane will remain in a plane section).

43-3.07 Reverse Curves

Reverse curves are two closely spaced simple curves with deflections in opposite directions. For this situation, it may not be practical to achieve a normal crown section between the curves. A plane section continuously rotating about its axis (e.g., the centerline) can be used between the two curves, if they are close enough together. The designer should adhere to the applicable superelevation development criteria for each curve. The following will apply to reverse curves:

1. Normal Section. The designer should not attempt to achieve a normal tangent section between reverse curves unless the normal section can be maintained for a minimum of two seconds of travel time, and the superelevation transition requirements can be met for both curves.

2. Continuously Rotating Plane. If a normal section is not provided, the pavement will be continuously rotated in a plane about its axis. In this case, the minimum distance

between the PT and PC will be that needed to meet the superelevation transition requirements for the two curves (e.g., distribution of superelevation runoff between the tangent and curve).

43-3.08 Bridges

If practical, horizontal curves and superelevation transitions should be avoided on bridges. The designer should place a curve on a bridge if this results in a more desirable alignment on either approaching roadway. In some cases, superelevation transitions are unavoidable on bridges; however, if properly designed and constructed, most bridges will operate adequately where this occurs.

43-4.0 HORIZONTAL SIGHT DISTANCE

43-4.01 Sight Obstruction (Definition)

Sight obstructions on the inside of a horizontal curve are defined as obstacles of considerable length which interfere with the line of sight on a continuous basis. These include guardrail, bridge railing, concrete median barrier, walls, cut slopes, wooded areas, buildings and high farm crops. In addition, a barrier to the line of sight should be assumed to be constructed on the right-of-way line. In general, point obstacles such as traffic signs and utility poles are not considered sight obstructions on the inside of horizontal curves. The designer must examine each curve individually to determine whether it is necessary to remove an obstruction, increase the offset to the obstruction, or increase the radius to obtain the required sight distance. However, the shoulder width should generally not exceed 3.6 m.

43-4.02 Curve Length Relative to Stopping Sight Distance

1. Curve Length > Stopping Sight Distance. Where the length of curve (L) is greater than the stopping sight distance (S) used for design, the needed clearance on the inside of the horizontal curve is calculated as follows:

$$M = R\left(1 - \cos\left(\frac{28.65\,S}{R}\right)\right) \qquad \text{(Equation 43-4.1)}$$

Where:

M = Middle ordinate, or distance from the center of the inside travel lane to the obstruction, ft

R = Radius of curve, ft

S = Stopping sight distance, ft

2. Curve Length < Stopping Sight Distance. Where the length of curve is less than or equal to the stopping sight distance, the design should be checked graphically or by utilizing a computational method.

43-4.02(01) Stopping Sight Distance (SSD)

At a minimum, SSD will be available throughout the horizontal curve. Figure 43-4A provides the horizontal clearance criteria (i.e., middle ordinate) for various combinations of stopping sight distance and curve radii. For those selections of S which fall outside of the figures (i.e., M > 50 ft and/or R < 165 ft), the designer should use Equation 43-4.1 to calculate the needed clearance. The Example on Figure 43-4C illustrates the determination of clearance requirements entering and exiting from a horizontal curve.

43-4.02(02) Other Sight Distance Criteria

At some locations, it may be warranted to provide SSD for trucks, decision sight distance or passing sight distance at the horizontal curve. Chapter Forty-two discusses candidate sites and provides design values for these sight distance criteria. These S values should be used in the basic equation to calculate M (Equation 43-4.1).

43-4.02(03) Entering/Exiting Portions (Typical Application)

The M values from Figures 43-4A and 43-4B apply between the PC and PT. In addition, some transition is needed on the entering and exiting portions of the curve. The designer should typically use the following steps:

1. Locate the point which is on the outside edge of shoulder and a distance of S/2 before the PC.

2. Locate the point which is a distance M measured laterally from the center of the inside travel lane at the PC.

3. Connect the two points located in Steps 1 and 2. The area between this line and the roadway should be clear of all continuous obstructions.

4. A symmetrical application of Steps 1 through 3 should be used beyond the PT.

The Example on Figure 43-4C illustrates the determination of clearance requirements entering and exiting from a curve.

43-4.03 Application

For application, the height of eye is 3'-6'' and the height of object is 2'-0''. Both the eye and object are assumed to be in the center of the inside travel lane. If the lane width for a ramp is wider than 12'-0'', the horizontal stopping sight distance should be calculated by placing the eye and object 6'-0'' from the edge of the lane on the inside of the curve.

43-4.04 Longitudinal Barriers

Longitudinal barriers (e.g., bridge railing, guardrail, median barrier) can cause sight distance problems at horizontal curves, because barriers are placed relatively close to the travel lane (often, 10 ft or less) and because their height is greater than 2 ft.

The designer should check the line of sight over a barrier along a horizontal curve and attempt, if practical, to locate the barrier such that it does not block the line of sight. The following should be considered:

1. Superelevation. The designer should account for the superelevation in the calculations.

2. Grades. The line of sight over a barrier may be improved for a driver on an upgrade and lessened on a downgrade.

3. Barrier Height. The higher the barrier, the more obstructive it will be to the line of sight.

Each barrier location on a horizontal curve will require an individual analysis to determine its impacts on the line of sight. The designer must determine the elevation of the driver eye (3'-6'' above the pavement surface), the elevation of the object (2'-0'' above the pavement surface) and

the elevation of the barrier where the line of sight intercepts the barrier run. If the barrier does block the line of sight to a 2'-0'' object, the designer should consider relocating the barrier or revising the horizontal alignment. If the barrier blocks the sight distance needed for minimum SSD on the mainline, it will be necessary to obtain a design exception.

43-5.0 DESIGN CONTROLS AND PROCEDURES

43-5.01 General Controls

As discussed in Chapter Forty-three, the design of horizontal alignment involves, to a large extent, complying with specific limiting criteria. These include minimum radii, superelevation rates and sight distance around curves. In addition, the designer should adhere to certain design principles and controls which will determine the overall safety of the facility and will enhance the aesthetic appearance of the highway. These design principles include the following:

1. Consistency. Alignment should be consistent. Sharp curves at the ends of long tangents and sudden changes from gentle to sharply curving alignment should be avoided.

2. Directional. Alignment should be as directional as possible consistent with physical and economic constraints. On divided highways a flowing line that conforms generally to the natural contours is preferable to one with long tangents that slash through the terrain. Directional alignment will be achieved by using the smallest practical central angles.

3. Use of Minimum Radii. The use of minimum radii should be avoided if practical.

4. High Fills. Avoid sharp curves on long, high fills. Under these conditions, it is difficult for drivers to perceive the extent of horizontal curvature.

5. Alignment Reversals. Avoid abrupt reversals in alignment ("S" or reverse curves). Provide a sufficient tangent distance between the curves to ensure proper superelevation transitions for both curves.

6. Broken-Back Curvature. Avoid where possible. This arrangement is not aesthetically pleasing, violates driver expectancy and creates undesirable superelevation development requirements.

7. Compound Curves. Avoid the use of compound curves on highway mainline. These may "fool" the driver in his/her effort to judge the sharpness of a horizontal curve.

8. Coordination with Natural/Man-Made Features. The horizontal alignment should be properly coordinated with the existing alignment at the ends of new projects, natural topography, available right-of-way, utilities, roadside development and natural/man-made drainage patterns.

9. Environmental Impacts. Horizontal alignment should be properly coordinated with environmental impacts (e.g., encroachment onto wetlands).

10. Intersections. Horizontal alignment through intersections may present special problems (e.g., intersection sight distance, superelevation development). See Chapter Forty-six for the design of intersections at-grade.

11. Coordination with Vertical Alignment. Chapter Forty-four discusses design principles for the coordination between horizontal and vertical alignment.

43-5.02 Coordination

In the design of horizontal alignment, the designer should be aware of his/her responsibility to communicate properly with other INDOT personnel (e.g., drafting, field survey):

1. Preparation of Plans. Part II of the *Indiana Design Manual* discusses the content and format of plan sheets, abbreviations, symbols, scales and the use of the Department's CADD system. The designer must ensure that the presentation of the horizontal alignment is consistent with Department practices.

2. Surveying. Part III of the *Indiana Design Manual* presents the Department's procedures and criteria for surveying practices.

3. Mathematical Computations. Section 43-6.0 presents numerous figures which provide the needed mathematical equations and techniques to make various computations for horizontal curves.

43-6.0 MATHEMATICAL DETAILS FOR HORIZONTAL CURVES

This Section presents mathematical details used by INDOT for various applications to the design of horizontal curves. Figure 43-6A summarizes the figures in Section 43-6.0.