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**CHAPTER FORTY-FOUR**

# VERTICAL ALIGNMENT

Chapter Forty-four presents the Department's criteria for the design of vertical alignment elements. This includes grades, climbing lanes, vertical curves and vertical clearances.

## 44-1.0 GRADES

### 44-1.01 Terrain (Definitions)

1. Level. Highway sight distances are either long or could be made long without major construction expense. The terrain is generally considered to be flat, which has minimal impact on vehicular performance.

2. Rolling. The natural slopes consistently rise above and fall below the roadway grade and, occasionally, steep slopes present some restriction to the desirable highway alignment. In general, rolling terrain generates steeper grades, causing trucks to reduce speeds below those of passenger cars.

3. Mountainous. Longitudinal and transverse changes in elevation are abrupt, and benching and side hill excavation are frequently required to provide the desirable highway alignment. Mountainous terrain aggravates the performance of trucks relative to passenger cars, resulting in some trucks operating at crawl speeds.

   The use of mountainous terrain criteria will not be permitted on a Federal-aid project because, even though a roadway may pass through a mountainous site, the area as a whole is still considered to be rolling terrain.

In general, if it is not clear which terrain designation to use (e.g., level versus rolling), the flatter of the two should be selected.

### 44-1.02 Maximum Grades

Chapters Fifty-three through Fifty-six provide the Department criteria for maximum grades based on functional classification, urban or rural location, type of terrain, design speed, and project scope of work. The maximum grades should be used only where absolutely necessary. Where practical, grades flatter than the maximum should be used.

## 44-1.03 Minimum Grades

The following provides the Department's criteria for minimum grades.

1. Uncurbed Road. It is desirable to provide approximately a 0.5% longitudinal grade. This allows for the possibility that the original crown slope is subsequently altered as a result of swell, consolidation, maintenance operations, or resurfacing. Level longitudinal gradients may be acceptable on a pavement which is adequately crowned to drain laterally.

2. Curbed Street. The centerline profile on a highway or a street with curbs should desirably have a minimum longitudinal gradient of 0.5%. Flatter or even level grades with rolling curb lines may be necessary in level terrain, where the adjacent development precludes the taking of additional right of way.

   On a curbed facility, the longitudinal gradient at the gutter line will have a significant impact on the pavement drainage characteristics (e.g., ponding, flow capture by grated inlets or catch basins). See Part IV for more information on pavement drainage.

## 44-1.04 Critical Length of Grade

Critical length of grade is the maximum length of a specific upgrade on which a loaded truck can operate without an unreasonable reduction in speed. The highway gradient in combination with the length of grade will determine the truck speed reduction on an upgrade. The following will apply to the critical length of grade.

1. Design Vehicle. A loaded truck, powered so that the mass/power ratio is about 120 kg/kW is representative of the size and type of vehicle normally used for design on a major route. For another highway, designing for the 120 kg/kW truck is not always cost-effective, especially on a route which has minimal truck traffic. Therefore, to better reflect the wide range of trucks, INDOT has adopted the following critical-length-of-grade criteria.

   a. Major Route. The 15 km/h reduction curve in Figure 44-1A, Critical Length of Grade for Truck, provides the critical length of grade for a 120 kg/kW truck. This figure should be used to determine the critical length of grade on a freeway, principal or minor arterial, or for a project on the extra heavy-duty highway system. See Chapter Sixty for a listing of extra heavy-duty routes. It also should be used on another road classification where significant numbers of large trucks are known to use the facility (e.g., coal-hauling routes).

b. Other Route. The 25 km/h reduction curve shown in Figure 44-1A provides the critical length of grade for a single-unit truck and the major portion of tractor-trailer trucks.

See Figure 44-1B, Critical Length of Grade for Recreational Vehicles.

2. Criteria. Figure 44-1A provides the critical lengths of grade for a given percent grade and acceptable truck speed reduction. This figure is based on an initial truck speed of 110 km/h, and representative truck (120 kg/kW).

3. Momentum Grades. Where an upgrade is preceded by a downgrade, a truck will often increase speed to make the climb. A speed increase of 10 km/h on a moderate downgrade (3-5%), and 15 km/h on a steeper downgrade (6-8%) of sufficient length are reasonable adjustments. These can be used in design to allow the use of a higher speed reduction curve in Figures 44-1A and 44-1B. However, these speed increases may not be attainable if traffic volumes are high enough that a truck may be behind a passenger vehicle when descending the momentum grade. Therefore, these increases in speed can only be considered if the highway has a LOS of C or better.

4. Measurement. Figures 44-1A and 44-1B are based upon length of tangent grade. If vertical curves are part of the length of grade, Figure 44-1C, Measurement for Length of Grade, illustrates how to determine an approximate equivalent tangent grade length.

5. Application. If the critical length of grade is exceeded, the grade should be flattened, if practical, or the need for a truck-climbing lane should be evaluated (see Section 44-2.0).

6. Highway Type. The critical length of grade criteria apply to a 2-lane or multi-lane highway, or to an urban or rural facility. Climbing lanes are not used as extensively on a freeway or multilane facility because they more frequently have sufficient capacity to handle their design year traffic without being congested. Vehicles can more easily move left to pass slower vehicles.

7. Example Problems. Examples 44-1.1 and 44-1.2 illustrate the use of Figure 44-1A to determine the critical length of grade. Example 44-1.3 illustrates the use of both Figures 44-1B and 44-1C. In the examples, the use of subscripts 1, 2, etc., indicate the successive gradients and lengths of grade on the highway segment.

* * * * * * * * * *

**Example 44-1.1**

Given: Level Approach

$G = +4\%$

L = 300 m (length of grade)
Rural Arterial

Problem: Determine if the critical length of grade is exceeded.

Solution: Figure 44-1A yields a critical length of grade of 350 m for a 15-km/h speed reduction. The grade is acceptable (300 < 350).

**Example 44-1.2**

Given: Level Approach
$G_1 = +2\%$
$L_1 = 500$ m
$G_2 = +5\%$
$L_2 = 200$ m
Rural Collector with significant number of heavy trucks

Problem: Determine if the critical length of grade is exceeded for the combination of grades $G_1$ and $G_2$

Solution: Using Figure 44-1A, $G_1$ yields a truck speed reduction of 9 km/h. $G_2$ yields approximately 11 km/h. The total of 20 km/h is greater than the allowable 15 km/h. Therefore, the critical length of grade is exceeded.

**Example 44-1.3**

Given: Figure 44-1D, Critical Length of Grade Calculations (Example 44-1.3), illustrates the vertical alignment on a low-volume, 2-lane rural collector with no large trucks.

Problem: Determine if the critical length of grade is exceeded for $G_2$ or the combination upgrade $G_3/G_4$.

Solution: Figure 44-1C presents the criteria for determining the length of grade. These are calculated for this example as follows:

$$L_2 = \frac{300}{4} + 180 + \frac{260}{4} = 320\ m$$

$$L_3 = \frac{260}{4} + 200 + \frac{125}{2} = 328\ m$$

$$L_4 = \frac{125}{2} + 150 + \frac{240}{4} = 273\ m$$

Read into Figure 44-1A using the 25 km/h reduction curve for $G_2$ (3%) and find a length of grade of 900 m. $L_2$ is less than this value and, therefore, the length of grade is not exceeded.

Read into Figure 44-1A for $G_3$ (3.5%) and $L_3$ = 328 m and find a speed reduction of 6 km/h. Read into Figure 44-1A for $G_4$ (2%) and $L_4$ = 273 m and find a speed reduction of 4 km/h. Therefore, the total speed reduction on the combination upgrade $G_3/G_4$ is 16 km/h. The allowable reduction is 25 km/h, therefore the critical length of grade is not exceeded.

* * * * * * * * * *

## 44-2.0 CLIMBING LANES

### 44-2.01 Warrants

A climbing lane may be warranted for trucks and recreational vehicles to allow a specific upgrade to operate at an acceptable level of service. The following criteria will apply.

#### 44-2.01(01) Two-Lane Highway

A climbing lane on a 2-lane, 2-way highway may be warranted if the following conditions are satisfied.

1. Upgrade traffic flow rate is in excess of 200 vehicles per hour.

2. Upgrade truck flow rate is in excess of 20 trucks per hour.

3. One of the following conditions exists.

    a. A 15 km/h or greater speed reduction is expected for a typical heavy truck.

    b. Level of Service (LOS) of E or F exists on the grade.

    c. A reduction of two or more levels of service is experienced when moving from the approach segment to the grade.

The upgrade flow rate is determined by multiplying the design hour volume by the directional distribution factor for the upgrade direction and dividing the result by the peak hour factor. See AASHTO *A Policy on Geometric Design of Highways and Streets* for more information including where to begin and end climbing lanes.

A climbing lane may also be warranted where the above criteria are not met if, for example, there is an adverse accident experience on the upgrade related to slow-moving trucks. However, on a designated recreational route, where a low percentage of trucks may not warrant a climbing lane, sufficient recreational-vehicle traffic may indicate a need for an additional lane. This can be evaluated by using Figure 44-1B, Critical Length of Grade for Recreational Vehicle. A climbing lane must be designed for each traffic direction, independently of the other.

### 44-2.01(02) Multi-Lane Highway

A climbing lane may be warranted on a multi-lane highway if the following conditions are satisfied.

1. The critical length of grade is less than the length of grade being evaluated; and

2. one of the following conditions exists:

    a. the LOS on the upgrade is E or F, or

    b. there is a reduction of one or more LOS when moving from the approach segment to the upgrade; and

3. the construction costs and the construction impacts (e.g., environmental, right of way) are considered reasonable.

Climbing lanes are generally not warranted on a 4-lane facility with directional volume below 1000 vehicles per hour per lane, regardless of the percentage of trucks. See AASHTO *A Policy on Geometric Design of Highways and Streets* for more information.

A climbing lane may also be warranted where the above criteria are not met if, for example, there is an adverse accident experience on the upgrade related to slow-moving trucks.

## 44-2.02 Capacity Procedures

### 44-2.02(01) Two-Lane Highway

The objective of the capacity analysis procedure is to determine if the warranting criteria in Section 44-2.01 are met for a 2-lane facility. This is accomplished by calculating the service flow rate for each LOS level (A through D) and comparing this to the actual flow rate on the upgrade. Because a LOS worse than D warrants a climbing lane, it is not necessary to calculate the service flow rate for LOS of E.

The operations on the grade should be analyzed using the procedures in the *Highway Capacity Manual* (HCM). In addition, the following should be considered.

1. To calculate the LOS, the following data should be compiled to complete the analysis.

    a. Average annual daily traffic (AADT) (mixed composition for year under design);

    b. the K factor (i.e., the proportion of AADT occurring in the design hour);

    c. the directional distribution (D) during the design hour (DHV);

    d. the truck factor (T) during the DHV (i.e., the % of trucks, buses, and recreational vehicles);

    e. the peak-hour factor (PHF);

    f. the design speed;

    g. lane and shoulder widths (m);

    h. percent grade;

    i. percent no-passing zones (based on the MUTCD criteria for striping of no-passing zones); see Chapter Seventy-six; and

    j. length of grade (km).

2. For a 2-lane highway, the type of truck is not a factor in determining the passenger car equivalent. Only the proportion of heavy vehicles (i.e., trucks, buses, or recreational vehicles) in the upgrade traffic stream is applicable.

3. For a highway with a single grade, the critical length of grade can be directly determined from Figure 44-1A, Critical Length of Grade for Truck, or Figure 44-1B, Critical Length of Grade for Recreational Vehicle. However, most highways have a continuous series of grades. Often, it is necessary to find the impact of a series of significant grades in succession. If several different grades are present, then a speed profile may need to be developed. Section 44-2.04 presents information on how to develop a truck speed profile.

### 44-2.02(02) Multi-Lane Highway

A climbing lane on a multi-lane highway is not as easily justified as that on a 2-lane facility because of the operational advantage of a multi-lane highway; i.e., a passenger car can pass a slow-moving truck without occupying an opposing lane of travel. As indicated in Section 44-2.01, INDOT has adopted criteria to warrant a truck-climbing lane on a multi-lane highway. These are based on the critical length of grade and on the LOS on the upgrade.

The calculation of LOS for an upgrade on a multi-lane highway is similar to that for a 2-lane highway (see Section 44-2.02(01) and the HCM). However, the various adjustment factors to calculate the service flow rate differ. This reflects the operational difference between a multi-lane and 2-lane facility. See the *Highway Capacity Manual* for the detailed capacity methodology.

## 44-2.03 Design

See Figure 44-2A, Design Criteria for Climbing Lane. The following should also be considered.

1. Design Speed. For a design speed equal to or greater than 90 km/h, use 90 km/h for truck design speed. For a speed less than 90 km/h, use the design speed.

2. Superelevation. For a horizontal curve, the climbing lane will be superelevated at the same rate as the adjacent travel lane.

3. Performance Curves. Figure 44-2B, Performance Curves for Heavy Trucks (120 kg/kW) for Deceleration on Upgrade, provides the deceleration rates for a heavy truck. Figure 44-2C, Speed-Distance Curves for Acceleration of a Typical Heavy Truck (120 kg/kW on Upgrade or Downgrade), provides the acceleration rates for a heavy truck.

4. End of Full-Width Lane. In addition to the criteria in Figure 44-2A, the available sight distance should be considered to the point where the truck will merge back into the through travel lane. At a minimum, this will be stopping sight distance. Desirably, the driver should have decision sight distance available to the merge point at the end of the taper to safely complete the maneuver, especially where the merge is on a horizontal or vertical curve.

## 44-2.04 Truck Speed Profile

The following example illustrates how to construct a truck speed profile and how to use Figures 44-2B and 44-2C.

* * * * * * * * * *

**Example 44-2.1**

Given: Level Approach
$G_1$ = +3% for 250 m (PVI to PVI)
$G_2$ = +5% for 1000 m (PVI to PVI)
$G_3$ = -2% beyond the composite upgrade ($G_1$ and $G_2$)
V = 100 km/h (design speed)
Rural Arterial on a Heavy Truck Route

Problem: Using the criteria in Figure 44-2A and Figure 44-2B, construct a truck speed profile and determine the beginning and ending points of the full-width climbing lane.

Solution: The following steps apply.

Step 1: Determine the beginning of the full-width climbing lane. From Figure 44-2A, desirably the beginning of the full-width lane will begin at the PVC and, at a minimum, at the PVT.

Step 2: Determine the truck speed on $G_1$, at 100-m increments, using Figure 44-2B and plot them in Figure 44-2D. Assume an initial truck speed of 90 km/h (see Figure 44-2B).

| Distance From $PVI_1$ (m) | Horizontal Distance on Figure 44-2B (m) | Truck Speed (km/h) | Comments |
|---|---|---|---|
| 0 | 0 | 90 | $PVI_1$ |
| 100 | 100 | 87 | |
| 200 | 200 | 85 | |
| 250 | 250 | 83 | $PVI_2$ |

Step 3: Determine the truck speed on $G_2$, at 100-m increments, using Figure 44-2B and plot them in Figure 44-2D, Truck Speed Profile (Example 44-2.1). From Step 2, the initial speed on $G_2$ is the final speed from $G_1$ (i.e., 83 km/h). Move left horizontally along the 83 km/h line to the 5% upgrade. This is approximately 500 m along the horizontal axis. This is the starting point for $G_2$.

| Distance From $PVI_1$ (m) | Horizontal Distance on Figure 44-2B (m) | Truck Speed (km/h) | Comments |
|---|---|---|---|
| 250 | 500 | 83 | $PVI_2$ |
| 350 | 600 | 79 | |
| 450 | 700 | 74 | |
| 550 | 800 | 68 | |

| | | | |
|---|---|---|---|
| 650 | 900 | 63 | |
| 750 | 1000 | 57 | |
| 850 | 1100 | 54 | |
| 950 | 1200 | 51 | |
| 1050 | 1300 | 48 | |
| 1150 | 1400 | 46 (1) | |
| 1250 | 1500 | 45 (1) | $PVI_3$ |

(1) The final crawl speed of the truck for a 5% upgrade.

Step 4: Determine the truck speed on $G_3$, at 100-m increments using Figure 44-2B until the point where the truck is able to accelerate to 75 km/h (minimum design speed for ending the climbing lane) and plot them in Figure 44-2D. The truck will have a speed of 45 km/h as it enters the 2% downgrade at the $PVI_3$. Read into Figure 44-2C at the 45 km/h point on the vertical axis over to the -2% line. This is approximately 0 m along the horizontal axis. The -2% line is followed to 75 km/h, which is approximately 300 m along the horizontal axis. Therefore, the truck will require 300 m, or 300 m - 0 m, from the $PVI_3$ to reach 75 km/h. The truck will require approximately an additional 500 m to reach 90 km/h (the desirable criteria).

| Distance From $PVI_1$ (m) | Horizontal Distance on Figure 44-2B (m) | Truck Speed (km/h) | Comments |
|---|---|---|---|
| 1250 | 0 | 45 | $PVI_3$ |
| 1350 | 100 | 59 | |
| 1450 | 200 | 68 | |
| 1550 | 300 | 75 | Minimum End |
| 1650 | 400 | 77 | |
| 1750 | 500 | 82 | |
| 1850 | 600 | 84 | |
| 1950 | 700 | 87 | |
| 2050 | 800 | 90 | Desirable End |

## 44-3.0 VERTICAL CURVES

### 44-3.01 Crest Vertical Curves

A crest vertical curve is in the shape of a parabola. The basic equations for determining the minimum length of a crest vertical curve are as described below.

### 44-3.01(01) Stopping Sight Distance

If the stopping sight distance is less than the vertical curve length ($S < L$),

$$L = \frac{AS^2}{100(\sqrt{2h_1} + \sqrt{2h_2})^2} = \frac{AS^2}{658} \qquad \text{(Equation 44-3.1)}$$

$$L = KA \qquad \text{(Equation 44-3.2)}$$

If the stopping sight distance is greater than or equal to the vertical curve length ($S \geq L$),

$$L = 2S - \frac{658}{A} \qquad \text{(Equation 44-3.3)}$$

where:

$L$ = length of vertical curve, m
$A$ = algebraic difference between the two tangent grades, %
$S$ = stopping sight distance, m
$h_1$ = height of eye above road surface, m
$h_2$ = height of object above road surface, m
$K$ = horizontal distance needed to produce a 1% change in gradient

$L$ will depend upon $A$ for the specific curve and upon the selected sight distance, height of eye, and height of object. The following discusses the selection of these values.

The principal control in the design of a crest vertical curve is to ensure that, at a minimum, stopping sight distance (SSD) is available throughout the curve. Figure 44-3A, K Values for Crest Vertical Curve (Stopping Sight Distance – Passenger Car), provides K values for various design speeds where $S < L$. The following discusses the application of the K value.

1. Passenger Car. The K value is calculated by assuming $h_1$ = 1.08 m, $h_2$ = 0.6 m, and $S$ = SSD in the basic equation for a crest vertical curve (Equation 44-3.1). The value represents the lowest acceptable sight distance on a facility. However, every reasonable effort should be made to provide a design in which the K value is greater than the value shown, where practical.

   Where $S \geq L$, any of the following methods may be used to check the stopping sight distance.

a. Using K Values. The K value provided is greater than or equal to the K value required and there are no changes to G1 or G2 in Figure 44-3A(1), Stopping Sight Distance Using K Values, Crest Vertical Curve.

b. Using Equation. Equation 44-3.3 shown above is only valid if there are no other vertical curves or angular breaks in the area shown in Figure 44-3A(1).

c. Using the AASHTO *Policy on Geometric Design of Highways and Streets*.

d. Checking Graphically. The eye should be placed at 1.08 m above the pavement and the height of the object at 0.6 m. The distance between the eye and the object that is unobstructed (by the road, backslope of a cut section, guardrail, etc.) is the stopping sight distance provided. It is necessary to check it in both directions for a 2-lane highway.

   If the stopping sight distance provided exceeds that required (even though the K value provided is less than the K value required), the K value will be treated as a Level Three design exception item instead of Level One.

If the K value provided exceeds the K value required, it is not necessary to perform either the equation check or the graphical check even though $S \geq L$.

2 Truck. The higher eye height for a truck, 2.4 m, offsets the longer stopping distance required on a vertical curve. Therefore, the K value for truck stopping sight distance need not be checked.

3. Minimum Length. The minimum length of a crest vertical curve in meters should be $0.6V$, where $V$ is the design speed in km/h, unless existing conditions make it impractical to use the minimum length criteria.

**44-3.01(02) Decision Sight Distance**

It may sometimes be warranted to provide decision sight distance in the design of a crest vertical curve. Section 42-2.0 discusses candidate sites and provides design values for decision sight distance. These $S$ values should be used in the basic equation for a crest vertical curve (Equation 44-3.1). In addition, the following will apply:

1. Height of Eye ($h_1$). For a passenger car, $h_1$ is 1.08 m.

2. Height of Object ($h_2$). Decision sight distance, is often predicated upon the same principles as stopping sight distance; i.e., the driver needs sufficient distance to see a 0.6-m-height object.

3. Passenger Car. Figure 44-3B, K Values for Crest Vertical Curve (Decision Sight Distance – Passenger Car), provides the K values using the decision sight distances shown in Section 42-2.0.

### 44-3.01(03) Drainage

Drainage should be considered in the design of a crest vertical curve where a curbed section or concrete barriers are used. Drainage problems are minimized if the crest vertical curve is sharp enough so that a minimum longitudinal grade of at least 0.3% is reached at a point about 15 m from either side of the apex. To ensure that this objective is achieved, the length of the vertical curve should be based upon a K value of 51 or less. For a crest vertical curve in a curbed section where this K value is exceeded, the drainage design should be more carefully evaluated near the apex.

For an uncurbed roadway section, drainage should not be a problem at a crest vertical curve. However, it is desirable to provide a longitudinal gradient of at least 0.15% at points about 15 m on either side of the high point. To achieve this, K must equal 100 or less.

See Part IV for more information on drainage.

## 44-3.02 Sag Vertical Curves

A sag vertical curve is in the shape of a parabola. Typically, it is designed to allow the vehicular headlights to illuminate the roadway surface (i.e., height of object = 0 m) for a given distance $S$. A headlight height, $h_3$, of 0.6 m, and a 1-deg upward divergence of the light beam from the longitudinal axis of the vehicle are assumed.

### 44-3.02(01) Stopping Sight Distance

These assumptions yield the following basic equations for determining the minimum length of a sag vertical curve. If the stopping sight distance, $S$, is less than the vertical curve length, $L$,

$$L = \frac{AS^2}{120 + 3.5S} \qquad \text{(Equation 44-3.4)}$$

If the stopping sight distance, $S$, is greater than or equal to the vertical curve length, $L$,

$$L = 2S - \frac{120 + 3.5S}{A} \qquad \text{(Equation 44-3.5)}$$

where:

$L$ = length of vertical curve, m
$A$ = algebraic difference between the two tangent grades, %
$S$ = sight distance, m
$K$ = horizontal distance needed to produce a 1% change in gradient

The length of the sag vertical curve will depend upon *A* for the specific curve and upon the selected sight distance and headlight height. The following sections discuss the selection of these values.

The principal control in the design of a sag vertical curve is to ensure that, at a minimum, stopping sight distance (SSD) is available for headlight illumination throughout the curve. Figure 44-3C, K Values for Sag Vertical Curve (Stopping Sight Distance – Passenger Car), provides K values for various design speeds where $S < L$. The following discusses the application of the K value.

1. Passenger Car. The K value is calculated by assuming $h_3 = 0.6$ m and $S$ = SSD in the basic equation for a sag vertical curve (Equation 44-3.4). The value represents the lowest acceptable sight distance on a facility. However, every reasonable effort should be made to provide a design in which the K value is greater than the value shown, where practical.

   Where the stopping sight distance is greater than or equal to the vertical curve length, any of the following methods may be used to check the stopping sight distance.

   a. Using K Values. The K value provided is greater than or equal to the K value required, and there are no changes to G1 or G2 as shown in Figure 44-3C(1), Stopping Sight Distance Using K Values, Sag Vertical Curve.

   b. Using Equation. Equation 44-3.5 shown above is only valid if there are no other vertical curves or angular breaks in the area shown in Figure 44-3C(1).

   c. Using the AASHTO *Policy on Geometric Design of Highways and Streets*.

   d. Checking Graphically. The headlight should be placed at 0.6 m above the pavement and the height of the object at 0 m. The light beam is assumed at a 1-deg upward divergence from the longitudinal axis of the vehicle. The distance between the headlight and the object that is unobstructed (by the road, backslope of a cut section, guardrail, etc.) is the stopping sight distance provided. It is necessary to check it in both directions for a 2-lane highway.

If the stopping sight distance provided exceeds that required (even though the K value provided is less than the K value required), the K value will be treated as a Level Three design exception item instead of Level One.

2. Truck. The higher headlight height for a truck, 1.2 m, offsets the longer stopping distance required on a vertical curve. Therefore, the K value for truck stopping sight distance need not be checked.

3. Minimum Length. The minimum length of a sag vertical curve in meters should be $0.6V$, where $V$ is the design speed in km/h, unless existing conditions make it impractical to use the minimum length criteria.

   One exception to this minimum length may apply in a curbed section. If the sag is in a "sump," the use of the minimum-length criteria may produce longitudinal slopes too flat to drain the stormwater without exceeding the criteria for the limits of ponding on the travel lane.

**44-3.02(02) Decision Sight Distance**

It may sometimes be warranted to provide decision sight distance in the design of a sag vertical curve. Section 42-2.0 discusses candidate sites and provides design values for decision sight distance. These $S$ values should be used in the basic equation for a sag vertical curve (Equation 44-3.5). The height of headlights, $h_3$, is 0.6 m. Figure 44-3D, K Values for Sag Vertical Curve (Decision Sight Distance – Passenger Car), provides K values using decision sight distance.

**44-3.02(03) Drainage**

Drainage should be considered in the design of a sag vertical curve where a curbed section or concrete barriers are used. Drainage problems are minimized if the sag vertical curve is sharp enough so that both of the following criteria are met.

1. A minimum longitudinal grade of at least 0.3% is reached at a point about 15 m from either side of the low point.

2. There is at least a 100-mm elevation differential between the low point in the sag and the two points 15 m to either side of the low point.

To ensure that the first objective is achieved, the length of the vertical curve should be based upon a K value of 51 or less. For a sag vertical curve in a curbed section where this K value is exceeded, the drainage design should be more carefully evaluated near the low point. For example, it may be necessary to install flanking inlets on either side of the low point.

For an uncurbed roadway section, drainage should not be a problem at a sag vertical curve. However, it is desirable to provide a longitudinal gradient of at least 0.15% at points about 15 m on either side of the low point. To achieve this, K must equal 100 or less.

See Part IV for more information on drainage.

### 44-3.02(04) Sight Distance at Undercrossing

Sight distance on a highway through a grade separation should be at least as long as the minimum stopping sight distance and preferably longer. Design of the vertical alignment is the same as at any other point on the highway except where a sag vertical curve underpasses a structure, as shown in Figure 44-3D, K Values for Sag Vertical Curve (Decision Sight Distance – Passenger Car). While not a frequent problem, the structure fascia may cut the line of sight and limit the sight distance to less than that otherwise attainable. It is generally practical to provide the minimum length of sag vertical curve at a grade separation structure. Even where the recommended grades are exceeded, the sight distance should not need to be reduced below the minimum values for stopping sight distance.

The available sight distance should sometimes be checked at an undercrossing, such as at a two-lane undercrossing without ramps, where it would be desirable to provide passing sight distance. Such checks are best made graphically on the profile, but may be performed through computations.

The general equations for sag vertical curve length at an undercrossing are as follows:

1. Sight distance, *S*, greater than vertical curve length, *L*,

$$L = 2S - \left\{ \frac{800[C - 0.5(h_1 + h_2)]}{A} \right\} \quad \text{(Equation 44-3.6)}$$

2. Sight distance, *S*, less than or equal to vertical curve length, *L*,

$$L = \frac{AS^2}{800\,[C - 0.5(h_1 + h_2)]} \quad \text{(Equation 44-3.7)}$$

For both equations, where:

$L$ = length of vertical curve, m
$S$ = sight distance, m
$A$ = algebraic difference in grades, %
$C$ = vertical clearance, m
$h_1$ = height of eye, m
$h_2$ = height of object, m

Using an eye height of 2.4 m for a truck driver and an object height of 0.6 m for the taillights of a vehicle, the following equation can be derived.

3. Sight distance , *S*, greater than vertical curve length, *L*,

$$L = 2S - \frac{800(C - 1.5)}{A} \qquad \text{(Equation 44-3.8)}$$

4. Sight distance, *S*, less than or equal to vertical curve length, *L*,

$$L = \frac{AS^2}{800(C - 1.5)} \qquad \text{(Equation 44-3.9)}$$

## 44-3.03 Vertical Curve Computations

The following will apply to the mathematical design of a vertical curve.

1. Definitions. Figure 44-3E, Vertical Curve Definitions, presents the common terms and definitions used in vertical curve computations.

2. Measurements. All measurements for a vertical curve are made on the horizontal or vertical plane, not along the profile grade. With the simple parabolic curve, the vertical offsets from the tangent vary as the square of the horizontal distance from the PVC or PVT. Elevations along the curve are calculated as proportions of the vertical offset at the point of vertical intersection (PVI). The necessary formulas for computing the vertical curve are shown in Figure 44-3F, Symmetrical Vertical Curve Equations. Figure 44-3G, Vertical Curve Computations (Example 44-3.1), provides an example of how to use these formulas.

3. Unsymmetrical Vertical Curve. Occasionally it is necessary to use an unsymmetrical vertical curve to obtain clearance on a structure or to satisfy some other design feature. This curve is similar to the parabolic vertical curve, except the curve does not vary symmetrically about the PVI. The necessary formulas for computing the unsymmetrical vertical curve are shown in Figure 44-3H, Unsymmetrical Vertical Curve Equations.

4. Vertical Curve Through Fixed Point. A vertical curve often must be designed to pass through an established point. For example, it may be necessary to tie into an existing transverse road or to clear existing structures. See Figure 44-3 I, Vertical Curve Computations. Figure 44-3J, Vertical Curve Computations (Example 44-3.2), illustrates an example on how to use these formulas.

> ** *PRACTICE POINTERS* **
>
> The profile grade should not be set too low. Field complaints about the profile grade having been set too low are much more common than complaints about it having been set too high.
>
> The K values for vertical curves should not be shown on the plans.

## 44-4.0 VERTICAL CLEARANCES

See Figure 44-4A, Minimum Vertical Clearances (New Construction or Reconstruction). Chapter Fifty-three provides additional information. Chapters Fifty-four through Fifty-six provide vertical clearance information for an existing highway.

## 44-5.0 DESIGN PRINCIPLES AND PROCEDURES

### 44-5.01 General Controls for Vertical Alignment

As discussed elsewhere in this Chapter, the design of vertical alignment involves, to a large extent, complying with specific limiting criteria. These include maximum and minimum grades, sight distance at vertical curves, and vertical clearances. In addition, the certain general design principles and controls should be adhered to which will determine the overall safety of the facility and will enhance the aesthetic appearance of the highway. These design principles for vertical alignment include the following:

1. Consistency. Use a smooth grade line with gradual changes, consistent with the type of highway and character of terrain, rather than a line with numerous breaks and short lengths of tangent grades.

2. Environmental Impacts. Vertical alignment should be properly coordinated with environmental impacts (e.g., encroachment onto wetlands). The Environment Planning and Engineering Division is responsible for evaluating environmental impacts.

3. Long Grades. On a long ascending grade, it is preferable to place the steepest grade at the bottom and flatten the grade near the top.

4. Intersection. Maintain moderate grades through an intersection to facilitate turning movements. See Chapter Forty-six for specific information on vertical alignment through an intersection.

5. Roller Coaster. The "roller-coaster" type of profile should be avoided. It may be proposed in the interest of economy, but it is aesthetically undesirable and may be hazardous.

6. Broken-Back Curvature. Avoid "broken-back" grade lines (two crest or sag vertical curves separated by a short tangent). One long vertical curve is more desirable.

7. Coordination with Natural or Man-Made Features. The vertical alignment should be properly coordinated with the natural topography, available right of way, utilities, roadside development, or natural or man-made drainage patterns.

8. Cut Section. Sag vertical curves should be avoided in a cut unless adequate drainage can be provided.

## 44-5.02 Coordination of Horizontal and Vertical Alignment

Horizontal and vertical alignment should not be designed separately, especially for a project on new alignment. Their importance demands that the interdependence of the two highway design features be carefully evaluated. This will enhance highway safety and improve the facility's operation. The following should be considered in the coordination of horizontal and vertical alignment.

1. Balance. Curvature and grades should be in proper balance. Maximum curvature with flat grades or flat curvature with maximum grades does not achieve this desired balance. A compromise between the two extremes produces the best design relative to safety, capacity, ease, and uniformity of operations and a pleasing appearance.

2. Coordination. Vertical curvature superimposed upon horizontal curvature (i.e., vertical and horizontal PIs at approximately the same station) generally results in a more pleasing appearance and reduces the number of sight distance restrictions. Successive changes in profile not in combination with the horizontal curvature may result in a series of humps visible to the driver for some distance, which may produce an unattractive design. However, under some circumstances, superimposing the horizontal and vertical alignment must be tempered somewhat by Items 3 and 4 as follows.

3. Crest Vertical Curve. Sharp horizontal curvature should not be introduced at or near the top of a pronounced crest vertical curve. This is undesirable because the driver cannot perceive the horizontal change in alignment, especially at night when headlight beams project straight ahead into space. This problem can be avoided if the horizontal curvature leads the vertical curvature or by using design values which well exceed the minimums.

4. Sag Vertical Curve. A sharp horizontal curve should not be introduced at or near the low point of a pronounced sag vertical curve or at the bottom of a steep vertical grade. Because visibility to the road ahead is foreshortened, only flat horizontal curvature will avoid an undesirable, distorted appearance. At the bottom of a long grade, vehicular speeds often are higher, particularly for trucks, and erratic operations may occur, especially at night.

5. Passing Sight Distance. The need for frequent passing opportunities and a higher percentage of passing sight distance may sometimes supersede the desirability of combining horizontal and vertical alignment. It may be necessary to provide a long tangent section to secure sufficient passing sight distance.

6. Intersection. At an intersection, horizontal and vertical alignment should be as flat as practical to provide a design which produces sufficient sight distance and gradients for vehicles to slow or stop. See Chapter Forty-six.

7. Divided Highway. On a divided facility with a wide median, it is frequently advantageous to provide independent alignments for the two one-way roadways. Where traffic justifies a divided facility, a superior design with minimal additional cost generally can result from the use of independent alignments.

8. Residential Area. The alignment should be designed to minimize nuisance factors to a neighborhood. Generally, a depressed facility makes the highway less visible and reduces the noise to adjacent residents. Minor adjustment to the horizontal alignment may increase the buffer zone between the highway and residential area.

9. Aesthetics. The alignment should be designed to enhance attractive scenic views of rivers, rock formations, parks, golf courses, etc. The highway should head into rather than away from those views that are considered to be aesthetically pleasing. The highway should fall towards those features of interest at a low elevation and rise toward those features which are best seen from below or in silhouette against the sky.

## 44-5.03 Profile Grade Line

### 44-5.03(01) General

The profile grade line is perhaps the roadway geometric characteristic which has the greatest impact on a facility's costs, aesthetics, safety, and operation. The profile grade is a series of tangent lines connected by parabolic vertical curves. It is typically placed along the roadway centerline of an undivided facility and on the two pavement centerlines on a divided facility.

The designer must evaluate many factors when establishing the profile grade line. These include the following:

1. maximum and minimum gradients;
2. sight distance criteria;
3. earthwork balance;
4. bridges and drainage structures;
5. high water levels;
6. drainage considerations;
7. water table elevations;
8. highway intersections and interchanges;
9. snow drifting;
10. railroad/highway crossings;
11. types of soil;
12. adjacent land use and values;
13. highway safety;
14. coordination with other geometric features (e.g., cross section);
15. topography/terrain;
16. truck performance;
17. right of way;
18. utilities;
19. urban or rural location;
20. aesthetics and landscaping;
21. construction costs.;
22. environmental impacts;
23. driver expectations;
24. airport flight paths (e.g., grades and lighting); and
25. pedestrian and handicapped accessibility.

The following sections discuss the establishment of the profile grade line in more detail.

### 44-5.03(02) Earthwork Balance

Where practical and where consistent with other project objectives, the the profile grade line should be designed to provide a balance of earthwork. This should not be achieved, however, at the expense of smooth grade lines and sight distance requirements at vertical curves. Ultimately, a project-by-project assessment will determine whether a project will be borrow, waste, or balanced.

The following should be considered in earthwork balance.

1. Basic Approach. The best approach to laying grade and balancing earthwork is to provide a significant length of roadway in embankment, to limit the number and amount of excavation areas. Long lengths of roadway in excavation with several short balance distances should be avoided.

2. Urban or Rural. Earthwork balance is typically a practical objective only in a rural area. In an urban area, other project objectives (e.g., limiting right-of-way impacts) typically have a higher priority than balancing earthwork. In addition, excavated materials from an urban project are often unsuitable for embankments.

3. Borrow Sites. The availability and quality of borrow sites in the project vicinity will impact the desirability of balancing the earthwork.

4. Mass Diagram. A mass diagram illustrates the accumulated algebraic sum of material within the project limits. Such a diagram is useful in balancing earthwork and calculating haul distances and quantities. The mass diagram may indicate the following:

    a. the most economical procedure for disposing of excavated material,

    b. whether material should be moved backward or forward, or

    c. whether borrowing or wasting is more economical than achieving earthwork balance.

    Typically, a mass diagram is not prepared by the designer It may be prepared and used by the contractor for construction operation.

5. Balance Length. The typical balance length is 600 m or longer. For an interchange, the balance points should be selected to incorporate the entire interchange.

6. Earthwork Computations. Chapter Seventeen discusses the proper methods to compute and record the project earthwork quantities.

### 44-5.03(03) Soils

The type of earth material encountered often influences the grade line at a certain location. If rock is encountered, for example, it may be more economical to raise the grade and reduce the rock excavation. Soils which are unsatisfactory for embankment or cause a stability problem in a cut area may also be determining factors in establishing a grade line. The development of the profile grade should be coordinated with the Materials and Tests Division, which will conduct a soils survey.

### 44-5.03(04) Drainage and Snow Drifting

The profile grade line should be compatible with the roadway drainage design and should minimize snow drift problems. The following will apply.

1. Culvert. The roadway elevation should meet the Department criteria for minimum cover at a culvert and minimum freeboard above the head water level at a culvert. See Part IV for more information on culvert design.

2. Coordination with Geometrics. The profile grade line must reflect compatibility between drainage design and roadway geometrics. These include the design of sag and crest vertical curves, spacing of inlets on a curbed facility, impacts on adjacent properties, superelevated curves, intersection design elements and interchange design elements. For example, a sag vertical curve should be avoided in a cut section, and a long crest vertical curve should be avoided on a curbed pavement.

3. Snow Drifting. Where practical, the profile grade line should be at least 1.0 m above the natural ground level to prevent snow from drifting onto the roadway and to promote snow blowing off the roadway.

4. Water Table. The profile grade line should be established such that the top of the subgrade elevation should be not less than 0.6 m above the water table at all points along any cross section within the paved roadway surface. The elevation of the water table typically can be found in the Geotechnical Report. If it is not practical to provide the 0.6-m clearance, the designer should meet with the Materials and Tests Division's pavement design engineer and geotechnical engineer to develop an alternative solution.

### 44-5.03(05) Erosion Control

To minimize erosion, the following should be considered relative to the grade line.

1. Minimize the number of deep cuts and high fill sections.

2. Conform to the contour and drainage patterns of the area.

3. Make use of natural land barriers and contours to divert runoff and confine erosion and sedimentation.

4. Minimize the amount of disturbance.

5. Make use of existing vegetation.

6. Reduce slope length and steepness and ensure that erosion is confined to the right of way and does not deposit sediment on or erode away adjacent land.

7. Avoid locations having high base erosion potential.

8. Avoid cut or fill sections in a seepage area.

**44-5.03(06) Bridges**

The design of profile grade lines must be carefully coordinated with any bridges within the project limits. The following will apply:

1. Vertical Clearance. The criteria in Chapters Fifty-three and Fifty-six and Section 44-3.0 must be met. When laying the preliminary grade line, an important element in determining available vertical clearance is the assumed structure depth. This will be based on the structure type, span lengths, and depth/span ratio. For preliminary design, a 6.2-m to 6.5-m distance should be assumed between the finished grade of the roadway and the finished grade of the bridge deck. For final design, the designer must coordinate with the bridge designer to determine the roadway and bridge grade lines.

2. Bridge Over Water. Where the proposed facility will cross a body of water, the bridge elevation must be consistent with the necessary waterway opening to meet the Department's hydraulic requirements. The designer must coordinate with the Design Division's Hydraulics Unit and bridge designer to determine the approach roadway elevation to meet the necessary bridge elevation.

3. Railroad Bridge. A proposed facility over a railroad must meet the applicable criteria (e.g., vertical clearances, structure type, and depth). See Chapter Sixty-nine for more information.

4. Highway Under Bridge. Where practical, the low point of a roadway sag vertical curve should not be within the shadow of the bridge. This will help minimize ice

accumulations, and it will reduce the ponding of water which may weaken the earth foundation beneath the bridge. To achieve these objectives, the low point of a roadway sag should be approximately 30 m from the bridge.

5. High Embankment. The impacts of high embankment on a structure should be considered. This will increase the span length thus increasing structure costs.

6. Low Point. It is desirable to locate the low point of a sag vertical curve off the bridge deck.

### 44-5.03(07) Distance Between Vertical Curves

A desirable objective on a rural facility is to provide at least 500 m between two successive PVIs. This objective only applies to a project which has a considerable length where implementation is judged to be practical.

### 44-5.03(08) Ties with Existing Highways

A smooth transition is needed between the proposed profile grade line of the project and the existing grade line of an adjacent highway section. The existing grade line should be considered for a sufficient distance beyond the beginning or end of a project to ensure adequate sight distance. A connection should be made which is compatible with the design speed of the new project and which can be used if the adjoining road section is reconstructed.