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CHAPTER FORTY-FOUR

VERTICAL ALIGNMENT

This Chapter provides the Department's criteria for the design of each vertical-alignment element. This includes grade, climbing lane, vertical curve, and vertical clearance.

44-1.0 GRADE

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 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. Steep slopes may restrict the desirable highway alignment. Rolling terrain generates steeper grades, causing trucks to reduce speeds to 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.

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 Grade

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

44-1.03 Minimum Grade

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

1. Uncurbed Road. It is desirable to provide a longitudinal grade of approximately 0.5%. This allows for the possibility that the original crown slope is subsequently altered as a result of swell, consolidation, maintenance operations, or resurfacing. A level longitudinal grade 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 grade of 0.5%. A flatter or level grade 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 grade 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 200 lb/hp is representative of the size and type of vehicle normally used for design on a major route. For another type of highway, designing for the 200 lb/hp 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 10-mph reduction curve shown in Figure 44-1A, Critical Length of Grade for Truck, provides the critical length of grade for a 200 lb/hp 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 type of road classification where significant numbers of large trucks are known to use the facility (e.g., coal-hauling route).

b. Other Route. The 15-mph 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 70 mph, and representative truck of 200 lb/hp.

3. Momentum Grade. Where an upgrade is preceded by a downgrade, a truck will often increase speed to make the climb. A speed increase of 10 mph on a moderate downgrade (3 to 5%), and 15 mph on a steeper downgrade (6 to 8%) of sufficient length are reasonable adjustments. These can be used in design to allow the use of a higher speed reduction curve from Figure 44-1A or 44-1B. However, this speed increase may not be attainable if traffic volume is high enough that a truck may be behind a passenger vehicle when descending the momentum grade. Therefore, the increase 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 a vertical curve is 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 divided highway, or to an urban or rural facility. A climbing lane is not used as extensively on a freeway or multilane facility since it more frequently has sufficient capacity to handle its design-year traffic without being congested. A faster vehicle can more easily move left to pass a slower vehicle.

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 grades and lengths of grade on the highway segment.

* * * * * * * * * *

Example 44-1.1

Given: Level Approach
$G = +4\%$

L = Length of grade of 1000 ft
Rural Arterial

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

Solution: Figure 44-1A yields a critical length of grade of 1150 ft for a 10-mph speed reduction. The grade is therefore acceptable (1000 ft < 1150 ft).

Example 44-1.2

Given: Level Approach
G_1 = +2%
L_1 = 1600 ft
G_2 = +5%
L_2 = 650 ft
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 5 mph. G_2 yields approximately 6 mph. The total of 11 mph is greater than the allowable 10 mph. Therefore, the critical length of grade is exceeded.

Example 44-1.3

Given: Figure 44-1D illustrates the vertical alignment on a low-volume, 2-lane rural highway 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 provides the criteria for determining the length of grade. This is calculated as follows for this example.

$$L_2 = \frac{1000}{4} + 600 + \frac{850}{4} = 1062\ ft$$

$$L_3 = \frac{850}{4} + 650 + \frac{410}{2} = 1068\ ft$$

$$L_4 = \frac{410}{2} + 500 + \frac{790}{4} = 903\ ft$$

Read into Figure 44-1B for G_2 (3%) and find a length of grade of 1800 ft. L_2 is less than this value, therefore the length of grade is not exceeded.

Read into Figure 44-1B for G_3 (3.5%) and L_3 = 1080 ft and find a speed reduction of 4 mph. Read into Figure 44-1B for G_4 (2%) and L_4 = 900 ft and find a speed reduction of 2 mph. Therefore, the total speed reduction on the combination upgrade G_3/G_4 is 6 mph. However, for a low-volume road, the designer may assume a 5-mph increase in truck speed for the 3% momentum grade, G_2, which precedes G_3. Therefore, the speed reduction may be as high as 15 mph before the combination grade exceeds the critical length of grade. Assuming the benefits of the momentum grade leads to the conclusion that the critical length of grade is not exceeded.

* * * * * * * * * *

44-2.0 CLIMBING LANE

44-2.01 Warrants

A climbing lane may be warranted for truck or recreational-vehicle traffic so that a specific upgrade can operate at an acceptable level of service. The following criteria will apply.

44-2.01(01) Two-Lane Highway

A climbing lane 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 10-mph 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 a climbing lane.

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) Divided Highway

A climbing lane may be warranted 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.

A climbing lane is 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 Procedure

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 percent of trucks, buses, and recreational vehicles);

    e. the peak-hour factor, *PHF*;

    f. the design speed;

    g. lane and shoulder width (ft);

    h. percent grade;

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

    j. length of grade (mi).

2. 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, the highway will usually have a continuous series of grades. It is necessary to find the impact of a series of significant grades in succession. If several different grades are present, a speed profile may need to be developed. Section 44-2.04 provides information on how to develop a truck speed profile.

44-2.02(02) Divided Highway

A climbing lane on a divided highway is not as easily justified as that on a 2-lane facility because of the operational advantage of divided highway. 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 divided highway. These are based on the critical length of grade and on the LOS on the upgrade.

The calculation of LOS for an upgrade is similar to that for a 2-lane highway; see Section 44-2.02(01) and the HCM. However, the adjustment factors required to calculate the service flow rate differ. This reflects the operational difference between a divided and a 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 of 55 mph or higher, use 55 mph for truck design speed. For a speed lower than 55 mph, 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 Curve. Figure 44-2B, Performance Curves for Heavy Truck (200 lb/hp) 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 (200 lb/hp) 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. 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 500 ft (PVI to PVI)
G_2 = +5% for 3500 ft (PVI to PVI)
G_3 = -2% beyond the composite upgrade (G_1 and G_2)
V = 60 mph (design speed)
Rural Arterial, Heavy-Truck Route

Problem: Using the criteria shown 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, 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 200-ft increments, using Figure 44-2B and plot them in Figure 44-2D. Assume an initial truck speed of 55 mph (see Figure 44-2B).

Distance From PVI_1 (ft)	Horizontal Distance on Figure 44-2B (ft)	Truck Speed (mph)	Comments
0	0	55	PVI_1
200	200	53	
400	400	51	
500	500	50	PVI_2

Step 3: Determine the truck speed on G_2, at 500-ft increments, using Figure 44-2B and plot them in Figure 44-2D. From Step 2, the initial speed on G_2 is the final speed from G_1 (i.e., 50 mph). Move left horizontally along the 50-mph line to the 5% upgrade. This is approximately 250 ft along the horizontal axis. This is the starting point for G_2.

Distance From PVI_1 (ft)	Horizontal Distance on Figure 44-2B (ft)	Truck Speed (mph)	Comments
500	1500	55	PVI_2
1000	2000	50	

1500	2500	45	
2000	3000	40	
2500	3500	36	
3000	4000	32	
3500	4500	30 (1)	
4000	5000	27 (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 500-ft increments, using Figure 44-2B until the point where the truck is able to accelerate to 45 mph (minimum design speed for ending the climbing lane) and plot them in Figure 44-2D. The truck will have a speed of 27 mph as it enters the 2% downgrade at the PVI_3. Read into Figure 44-2B at the 27-mph point on the vertical axis over to the -2% line. This is approximately 0 ft along the horizontal axis. The -2% line is followed to 45 mph, which is approximately 1000 ft along the horizontal axis. Therefore, the truck will require 1000 ft (1000 ft - 0 ft) from the PVI_3 to reach 45 mph. The truck will require approximately an additional 1200 ft to reach 55 mph (the desirable criterion).

Distance From PVI_1 (ft)	Horizontal Distance on Figure 44-2C (ft)	Truck Speed (mph)	Comments
4000	0	27	PVI_3
4500	500	40	
5000	1000	45	Minimum End
5500	1500	50	
6000	2000	53	
6500	2500	55	Desirable End

* * * * * * * *

44-3.0 VERTICAL CURVE

44-3.01 Crest Vertical Curve

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, S, is less than the vertical curve length, L,

$$L = \frac{AS^2}{100\left(\sqrt{2h_1} + \sqrt{2h_2}\right)^2} = \frac{AS^2}{2158} \qquad \text{(Equation 44-3.1)}$$

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

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

$$L = 2S - \frac{2158}{A} \qquad \text{(Equation 44-3.3)}$$

where:

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

The length of the crest vertical curve 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 Value for Crest Vertical Curve (Stopping Sight Distance – Passenger Car), provides the K value for the design speed where $S < L$. The following discusses the application of the K value.

1. Passenger Car. The K value is calculated by assuming h_1 = 3.5 ft, h_2 = 2 ft, 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 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 Value. The K value provided is greater than or equal to the K value required and there are no changes to G_1 or G_2 in Figure 44-3A(1), Crest Vertical Curve Stopping Sight Distance Using K Value.

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 3.5 ft above the pavement and the height of the object at 2 ft. 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, 7.6 ft, 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 feet should be 3*V*, where *V* is the design speed in mph, 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 3.5 ft

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 2-ft-height object.

3. Passenger Car. Figure 44-3B, *K* Value for Crest Vertical Curve (Decision Sight Distance – Passenger Car), provides the *K* value using the decision sight distance 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 barrier is 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 50 ft 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 167 or less. For a crest vertical curve in a curbed section where this *K* value is exceeded, the drainage design should be 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 50 ft on either side of the high point. To achieve this, *K* must equal 300 or less.

See Part IV for more information on drainage.

44-3.02 Sag Vertical Curve

A sag vertical curve is in the shape of a parabola. It is designed to allow the vehicular headlights to illuminate the roadway surface (i.e., height of object = 0 ft) for a given distance *S*. A headlight height, h_3, of 2 ft, 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 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*,

$$L = \frac{AS^2}{400 + 3.5S} \qquad \text{(Equation 44-3.4)}$$

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

$$L = 2S - \frac{400 + 3.5S}{A} \qquad \text{(Equation 44-3.5)}$$

where:

L = length of vertical curve, ft
A = algebraic difference between the two tangent grades, %
S = sight distance, ft
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 discusses 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* Value for Sag Vertical Curve (Stopping Sight Distance – Passenger Car), provides the *K* value for the design speed where $S < L$. The following discusses the application of the *K* value.

1. Passenger Car. The *K* value is calculated by assuming h_3 = 2 ft and S = SSD in the 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* Value. The *K* value provided is greater than or equal to the *K* value required, and there are no changes to G_1 or G_2 as shown in Figure 44-3C(1), Sag Vertical Curve Stopping Sight Distance Using *K* Value.

   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 2 ft above the pavement and the height of the object at 0 ft. 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, 4 ft, 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 feet should be 3.2*V*, where *V* is the design speed in mph, 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 equation for a sag vertical curve (Equation 44-3.5). The height of headlights, h_3, is 2 ft. Figure 44-3D, *K* Value for Sag Vertical Curve (Decision Sight Distance – Passenger Car), provides the *K* value 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 50 ft from either side of the low point.

2. There is at least a 0.25-ft elevation differential between the low point in the sag and the two points 50 ft 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 167 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 50 ft on either side of the low point. To achieve this, *K* must equal 300 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* Value 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 practical to provide the minimum length of sag vertical curve at a grade separation structure. Where the recommended grades are exceeded, the sight distance should not be reduced below the minimum value 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 a check is best made graphically on the profile, but may be performed through computations.

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

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

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

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

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

For both equations, where:

L = length of vertical curve, ft
S = sight distance, ft
A = algebraic difference in grades, %
C = vertical clearance, ft

h_1 = height of eye, ft
h_2 = height of object, ft

Using an eye height of 7.6 ft for a truck driver and an object height of 2 ft for the taillights of a vehicle, the following equation can be derived.

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

$$L = 2S - \frac{800(C-5)}{A} \qquad \text{(Equation 44-3.8)}$$

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

$$L = \frac{AS^2}{800(C-5)} \qquad \text{(Equation 44-3.9)}$$

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, provides 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. It may be 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 an existing structure. See Figure 44-3 I, Vertical-Curve

Computations. Figure 44-3J, Vertical-Curve Computations (Example 44-3.2), illustrates an example of 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 CLEARANCE

See Figure 44-4A, Minimum Vertical Clearance (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 PROCEDURE

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 a vertical curve, and vertical clearance. The following design principles and controls should be considered 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 Impact. Vertical alignment should be properly coordinated with environmental impact (e.g., encroachment onto wetlands). The Office of Environmental Services is responsible for evaluating environmental impacts.

3. Long Grade. 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 a broken-back grade line of 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 Feature. 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. A sag vertical curve should be avoided in a cut section 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) 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, sometimes 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 can result from the use of independent alignments.

8. Residential Area. The alignment should be designed to minimize nuisance factors to a neighborhood. 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 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 placed along the roadway centerline of an undivided facility or on the two pavement centerlines of a divided facility.

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

1. maximum and minimum grades;
2. sight-distance criteria;
3. earthwork balance;
4. bridge or drainage structure;
5. high-water level;
6. drainage considerations;
7. water-table elevations;
8. highway intersection or interchange;
9. snow drifting;
10. railroad-highway crossing;
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 or 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 discusses 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 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 a vertical curve. 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 a practical objective only in a rural area. In an urban area, other project objectives (e.g., limiting right-of-way impacts) have a higher priority than balancing earthwork. 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.

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

5. Balance Length. A balance length is 2000 ft 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 Office of Materials Management, 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 drifting problems. The following will apply.

1. Culvert. The roadway elevation should satisfy 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 3 ft 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 2 ft above the water table at all points along the cross section within the paved roadway surface. The elevation of the water table can be found in the Geotechnical Report. If it is not practical to provide the 2-ft clearance, the designer should meet with the Pavement Engineering Office manager 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) Bridge

The design of the profile-grade line must be coordinated with each bridge 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 satisfied. In laying the preliminary grade line, an 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 20-ft to 21-ft 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 satisfy the Department's hydraulic requirements. The designer must coordinate with the Production Management Division's Hydraulics Team and the bridge designer to determine the approach-roadway elevation to complement the necessary bridge elevation.

3. Railroad Bridge. A proposed facility over a railroad must satisfy 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 100 ft 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.

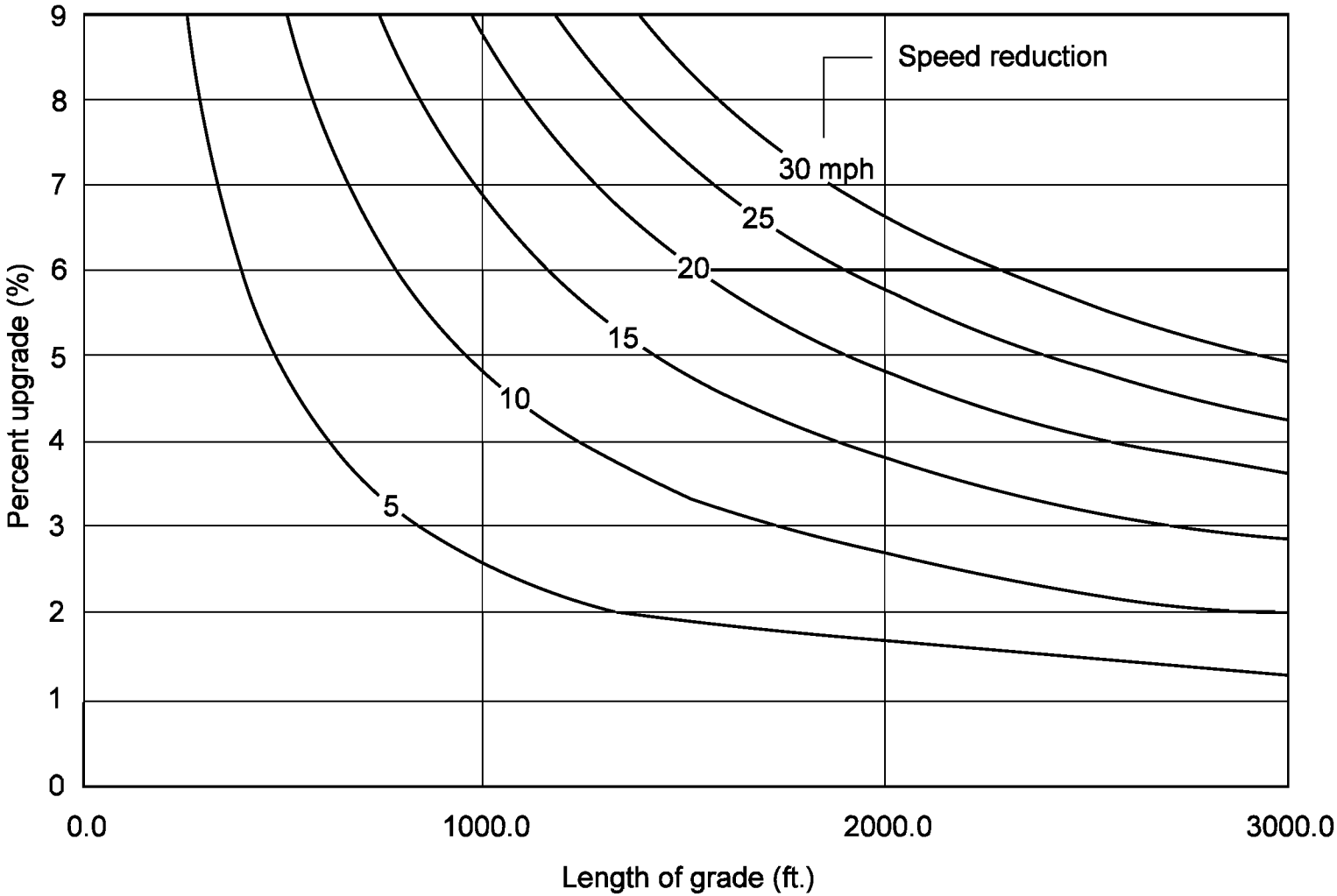
6. Low Point. It is desirable to locate the low point of a sag vertical curve off the bridge deck.

44-5.03(07) Distance Between Vertical Curves

A desirable objective on a rural facility is to provide at least 1500 ft between two successive PVIs. This objective applies only to a project which has a considerable length where implementation is judged to be practical.

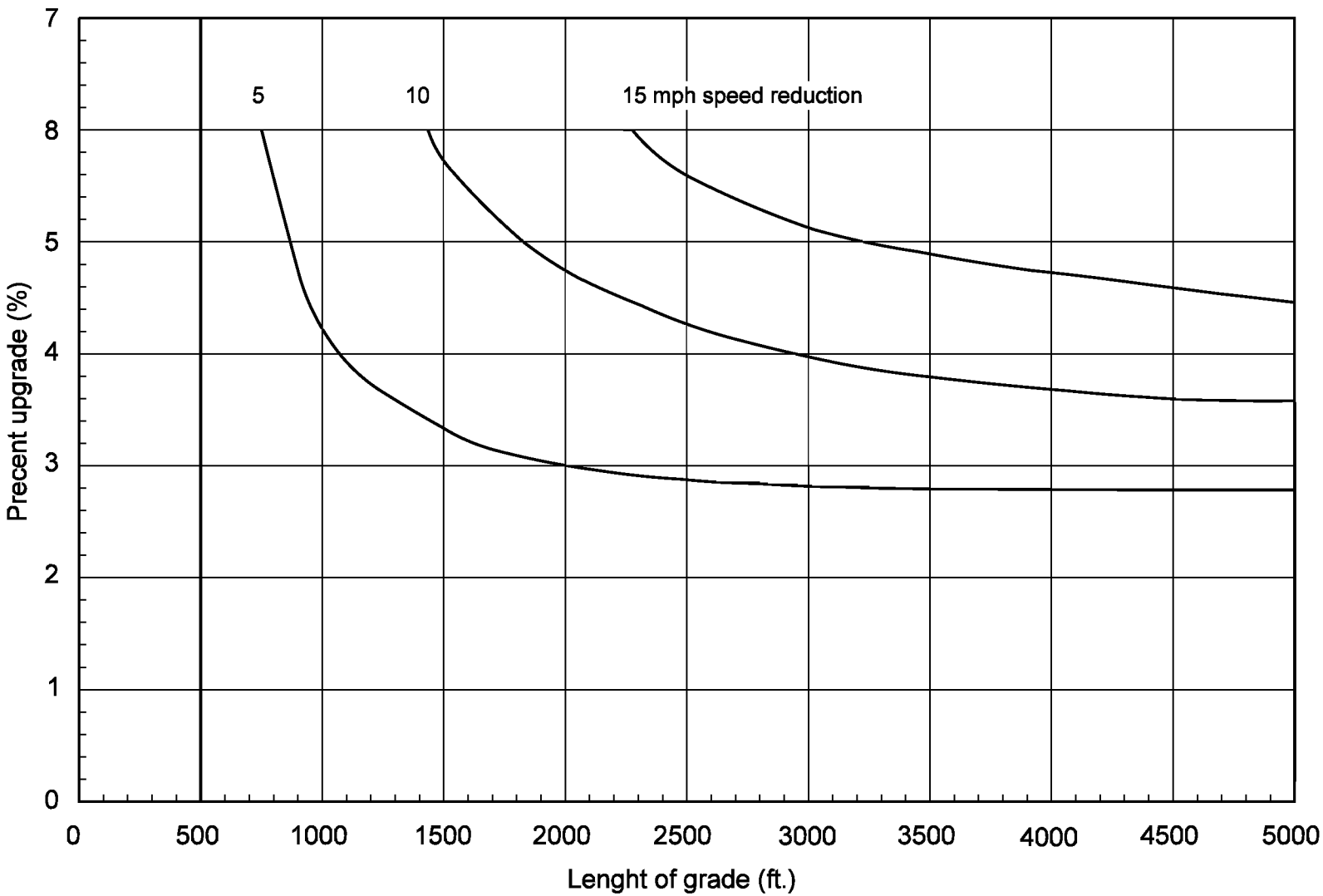
44-5.03(08) Ties with Existing Highways

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.



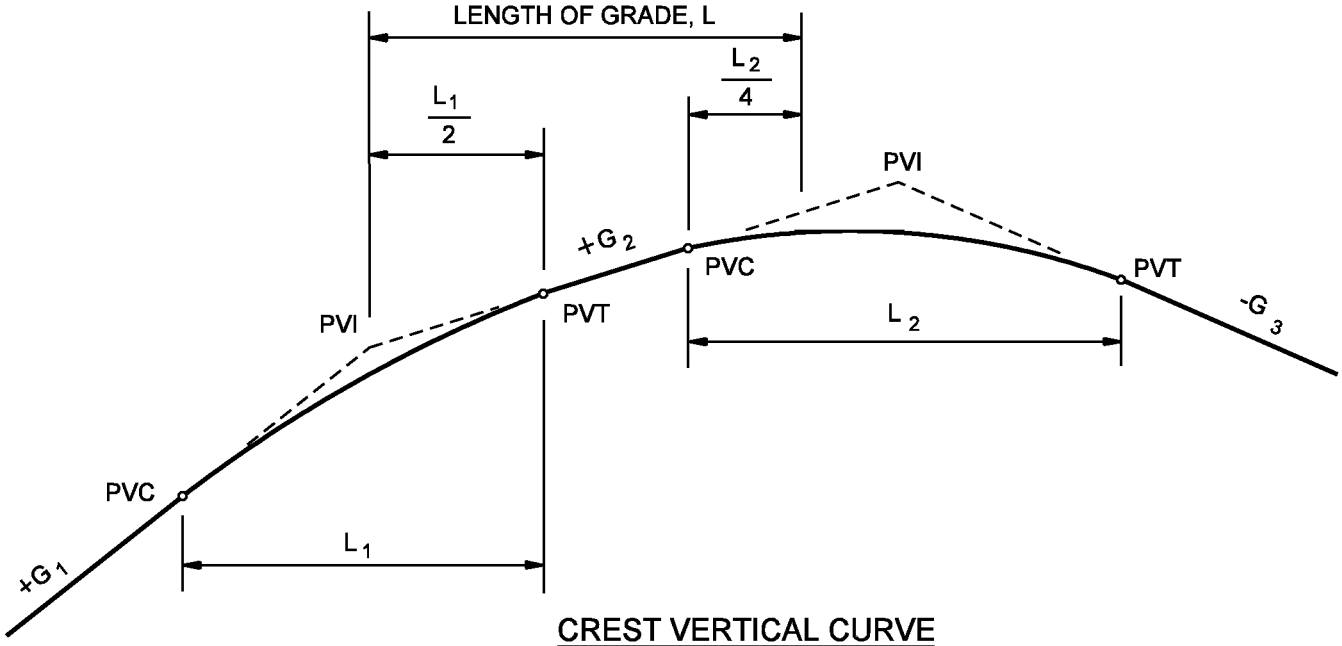
Critical Lengths of Grade for Design, Assumed Typical Heavy Truck of 200 lb/hp, Entering Speed = 70 mph

Figure 44-1A

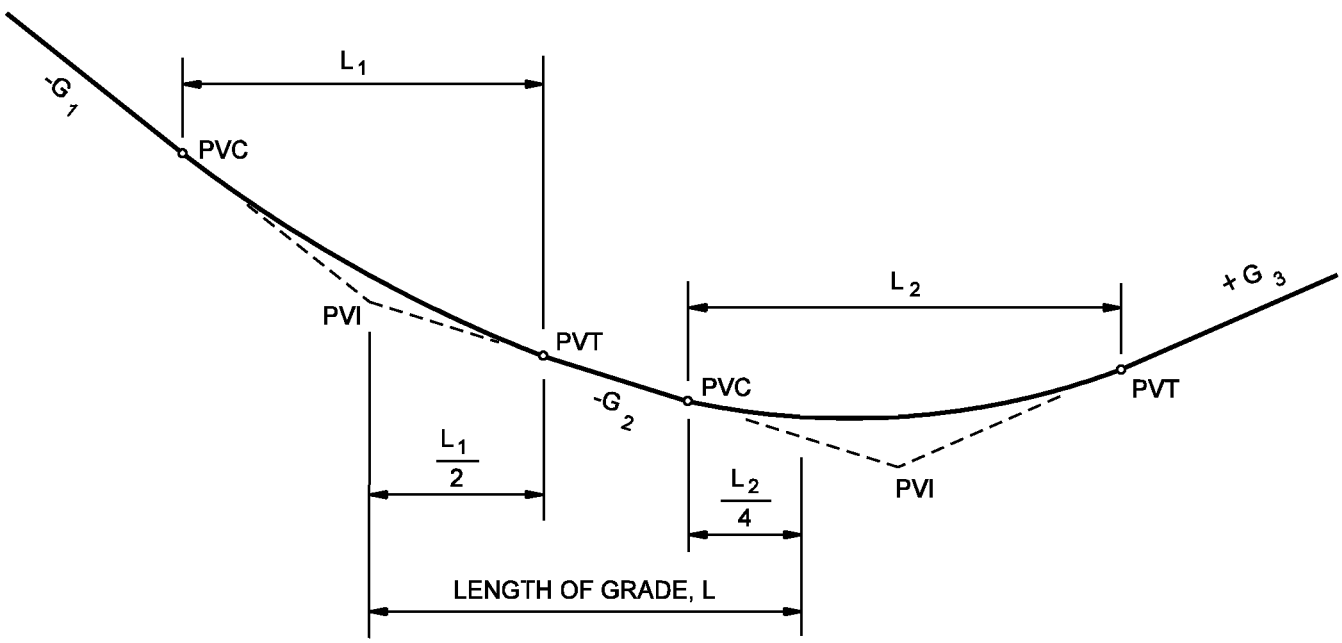


Critical Lengths of Grade Using an Approach Speed of 55 mph for Typical Recreational Vehicle

Figure 44-1B



CREST VERTICAL CURVE



SAG VERTICAL CURVE

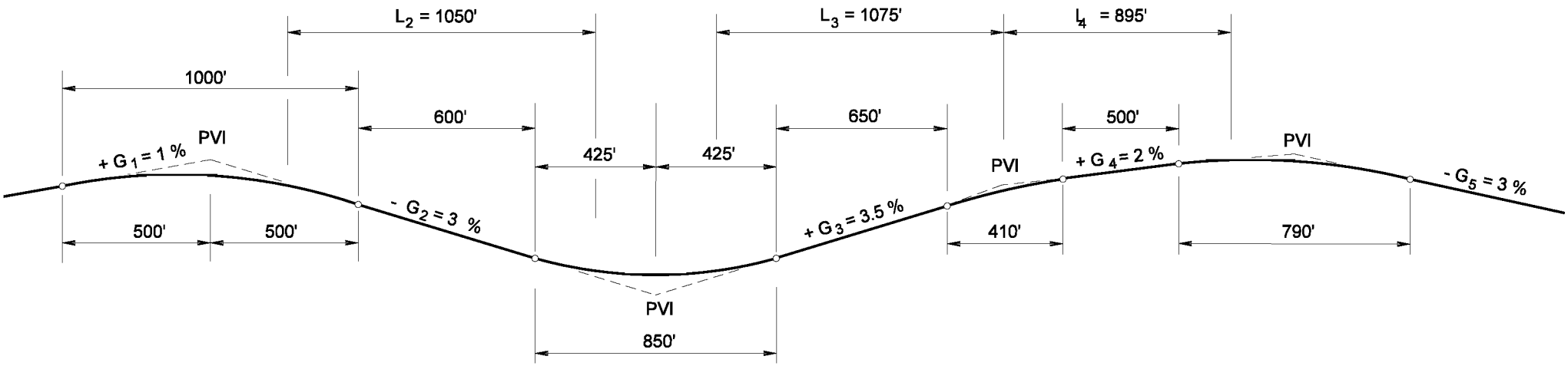
Notes:

1. *For verticao curves where the two tangent grades are in the same direction (both upgrades or both downgrades), 50% of the curve length will be part of the length of grade.*

2. *For vertical curves where the two tagent grades are in opposite directions (one grade up and one grade down), 25% of the curve length will be part of the length of the grade.*

MEASUREMENT FOR LENGTH OF GRADE

Figure 44-1C



CRITICAL LENGTH OF GRADE CALCULATIONS
(Example 44-1.3)

Figure 44-1D

DESIGN ELEMENT	DESIRABLE	MINIMUM
Lane Width	12 ft	Same as that required for through lane
Shoulder Width	Same as approach roadway	Freeway: Same as approach roadway (1) Non-Freeway: 4 ft paved
Cross Slope on Tangent	3%	2%
Beginning of Full-Width Lane	Near the PVC of the vertical curve preceding the grade.	At the PVT of the grade.
End of Full-Width Lane (2)	To where truck has reached highway design speed or 55 mph, whichever is lower.	To where truck has reached 10 mph below highway design speed or 45 mph, whichever is lower.
Entering Taper	100 ft	100 ft
Exiting Taper	50:1	500 ft
Minimum Full-Width Length	n/a	1000 ft

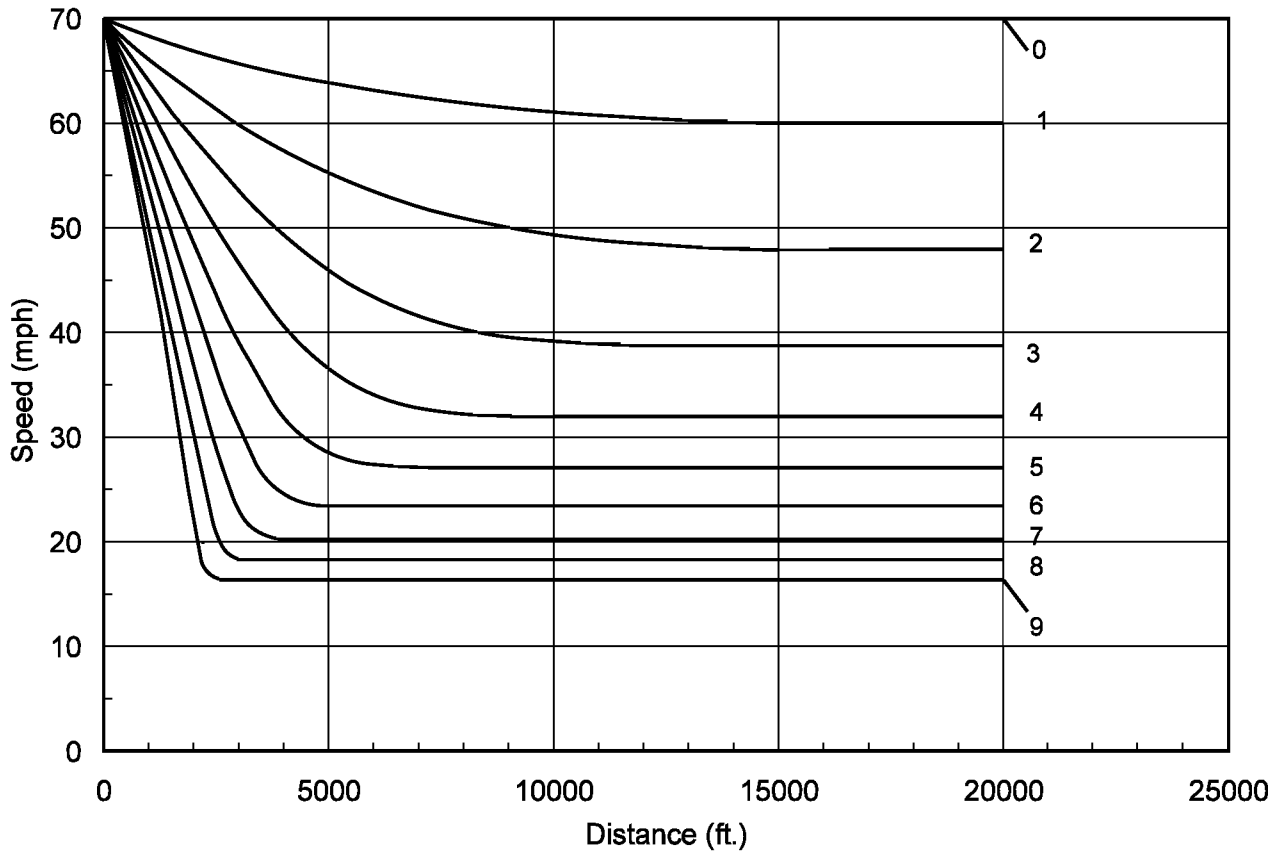
Notes:

(1) On a reconstruction project, a 6-ft shoulder may be used.

(2) Use Figure 44-2B to determine truck deceleration rate. Use Figure 44-2C to determine truck acceleration rate. Also, see discussion in Section 44-2.03.

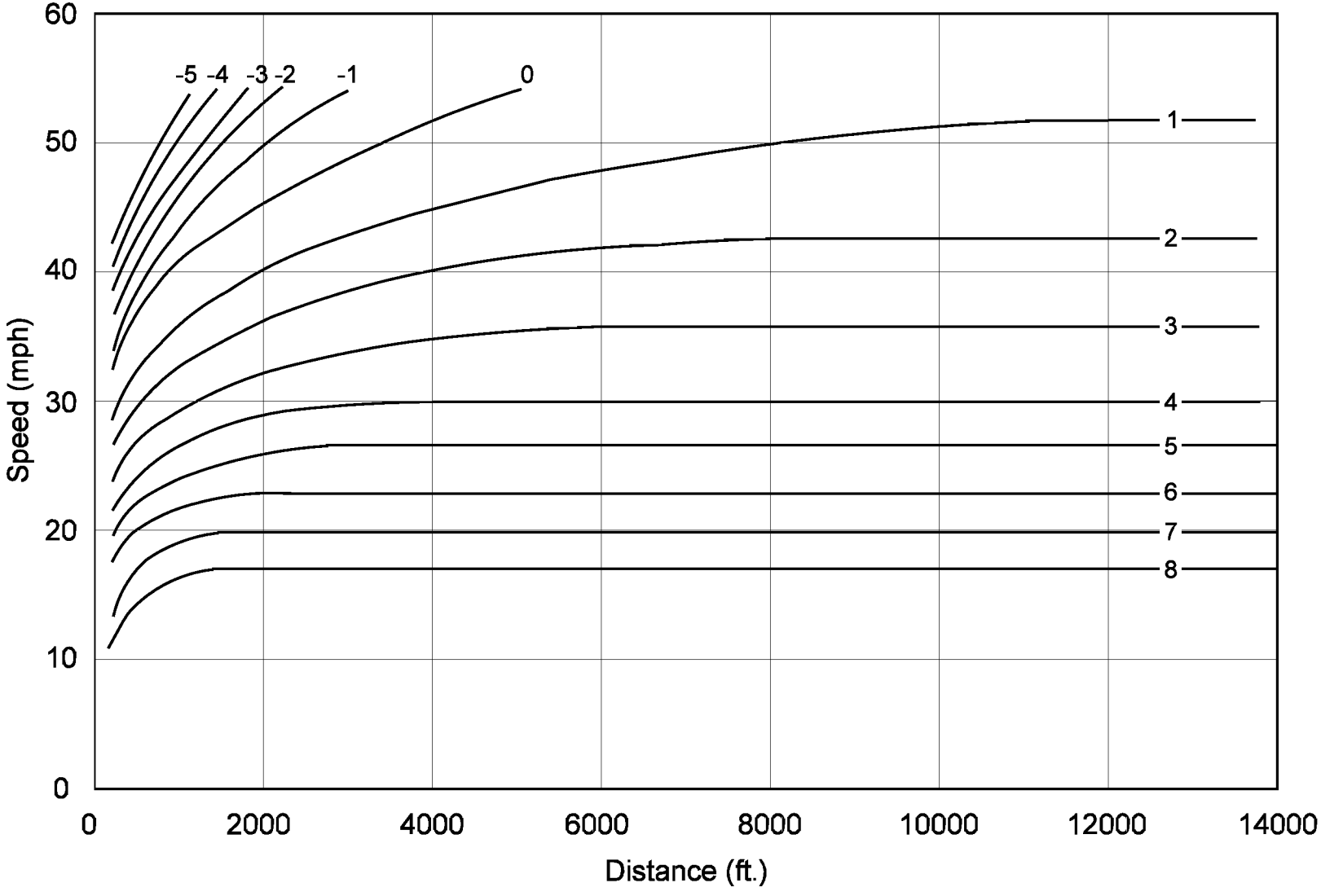
DESIGN CRITERIA FOR CLIMBING LANE

Figure 44-2A



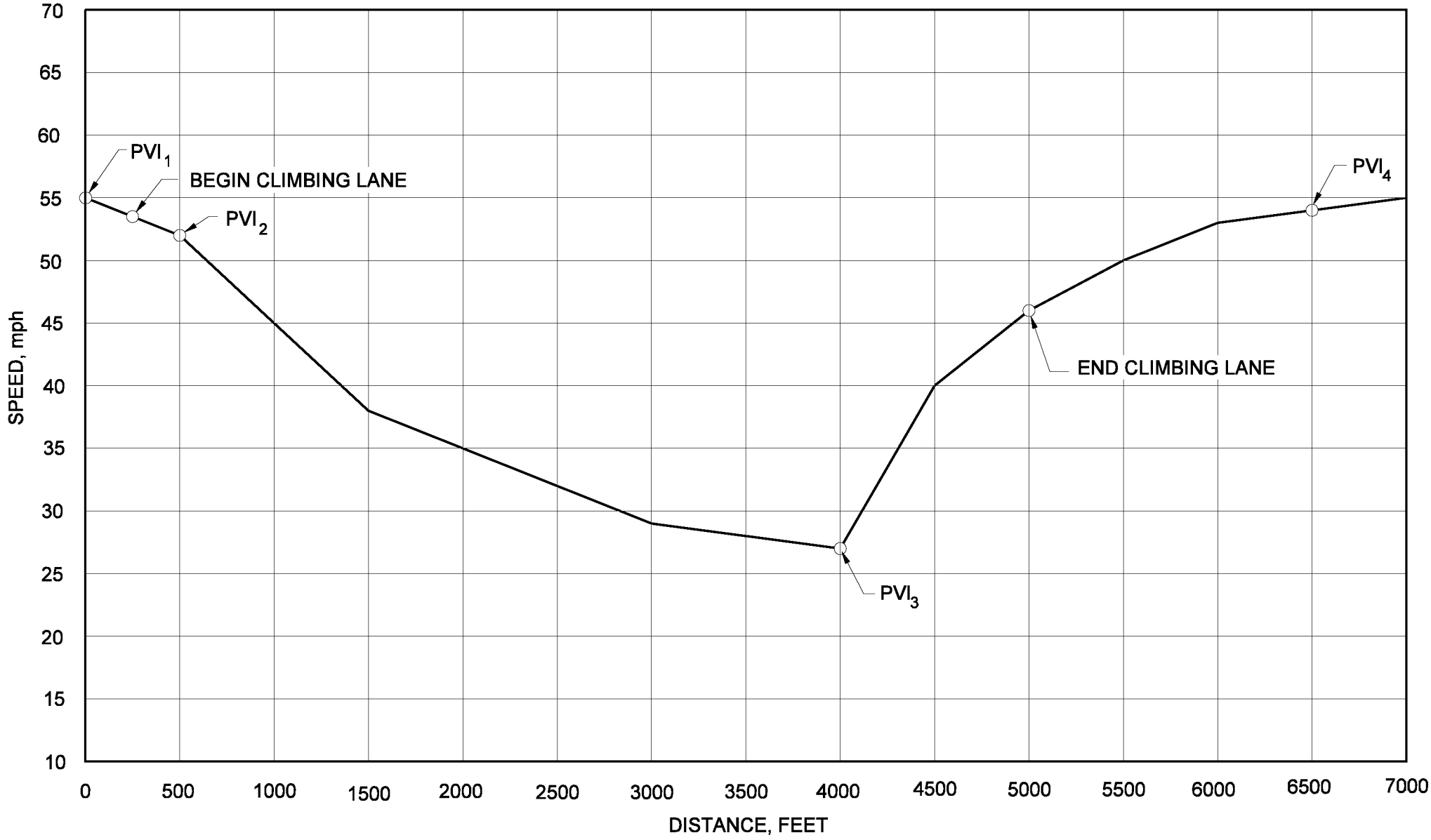
Speed-Distance Curves for a Typical Heavy Truck of 200 lb/hp for Deceleration on Upgrades

Figure 44-2B



Speed-Distance Curves for Acceleration of a Typical Heavy Truck of 200 lb/hp on Ugrades and Downgrades

Figure 44-2C



TRUCK SPEED PROFILE
(Example 44-2.1)

Figure 44-2D

DESIGN SPEED (mph)	ROUNDED SSD FOR DESIGN [1] (ft)		CALCULATED *K* VALUE [2]		*K* VALUE ROUNDED FOR DESIGN	
	Des.	Min.	Des.	Min.	Des.	Min.
15	115	80	6.1	3.0	7	3
20	155	115	11.1	6.1	12	7
25	200	155	18.5	11.1	19	12
30	250	200	29.0	18.5	29	19
35	305	250	43.1	29.0	44	29
40	360	305	60.1	43.1	61	44
45	425	360	83.7	60.1	84	61
50	495	425	113.5	83.7	114	84
55	570	495	150.6	113.5	151	114
60	645	570	192.8	150.6	193	151
65	730	645	246.9	192.8	247	193
70	820	730	312.6	246.9	312	247

Notes:

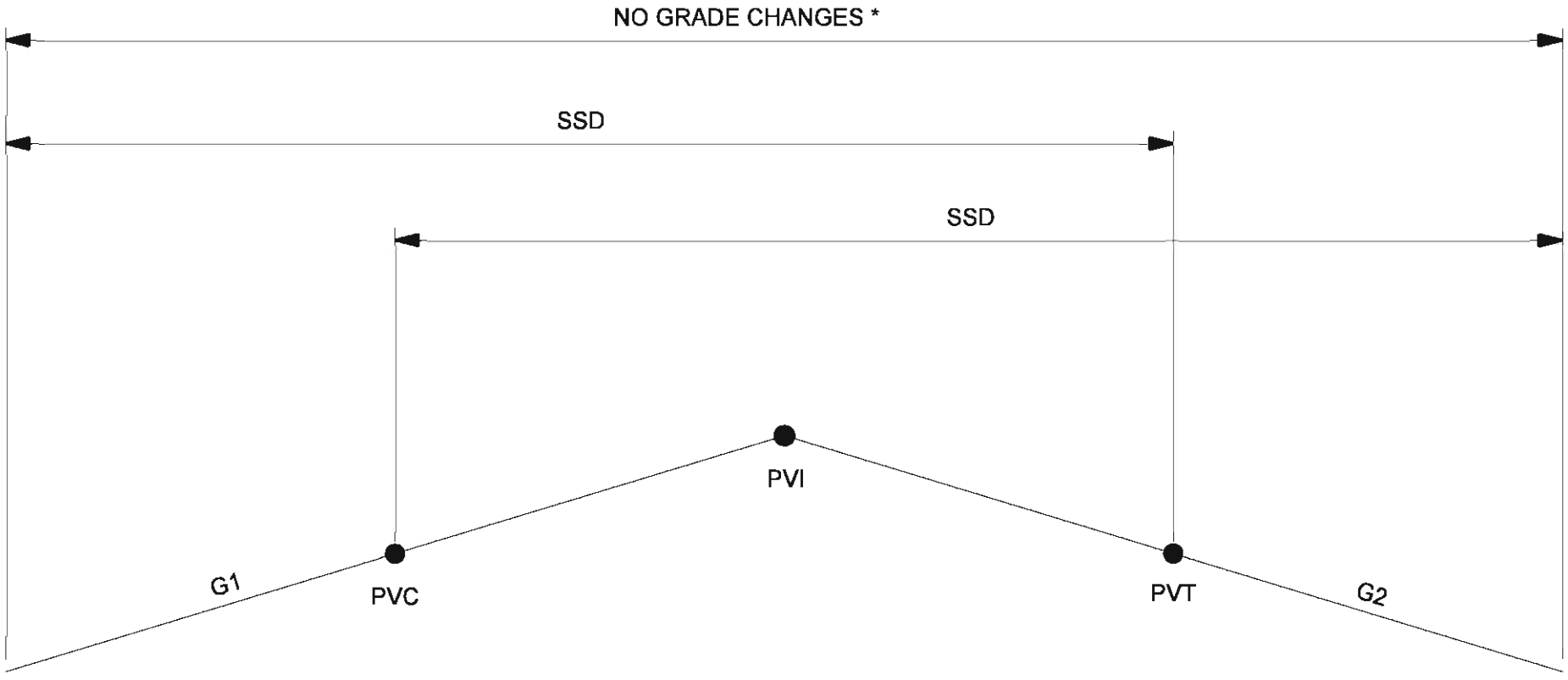
[1] *Stopping sight distance (SSD) is from Figure 42-1A.*

[2] *The K value is calculated using the rounded value for design stopping sight distance, eye height of 3.5 ft, and object height of 2 ft.*

3. If curbs are present, and K > 167, proper pavement drainage should be ensured near the high point of the curve.

_K_ VALUE FOR CREST VERTICAL CURVE
(Stopping Sight Distance – Passenger Car)

Figure 44-3A



* No other vertical curves or angular breaks within this zone.

STOPPING SIGHT DISTANCE CHECK USING K-VALUES,
CREST VERTICAL CURVE

Figure 44-3A(1)

Design Speed (mph)	Avoidance Maneuver A (Stop on Rural Road)		Avoidance Maneuver B (Stop on Urban Road)		Avoidance Maneuver C (Speed/Path/ Direction Change on Rural Road)		Avoidance Maneuver D (Speed/Path/ Direction Change on Suburban Road)		Avoidance Maneuver E (Speed/Path/ Direction Change on Urban Road)	
	DSD (ft)	*K* Value	DSD (ft)	*K* Value	DSD (ft)	*K* Value	DSD (ft)	*K* Value	DSD (ft)	*K* Value
20	90	11	270	54	300	62	360	77	415	92
25	110	15	335	72	375	82	450	101	515	121
30	220	23	490	112	450	94	535	133	620	178
35	275	35	590	162	525	128	625	181	720	241
40	330	51	690	221	600	167	715	237	825	315
45	395	73	800	297	675	211	800	297	930	401
50	465	100	910	384	750	261	890	367	1030	492
55	535	133	1030	492	865	347	980	445	1135	597
60	610	173	1150	613	990	454	1125	587	1280	759
65	695	224	1275	754	1050	511	1220	690	1365	864

Notes:

1. *See Section 42-2.0 for decision sight distances (DSD).*
2. *The K value is calculated using the rounded value for design decision sight distance, eye height of 3.5 ft, and object height of 2 ft.*

$$K = \frac{DSD^{2}}{2158}$$

3. *If curbs are present and K > 167, proper pavement drainage should be ensured near the high point of the curve.*

_K_ VALUE FOR CREST VERTICAL CURVE
(Decision Sight Distance – Passenger Car)

Figure 44-3B

DESIGN SPEED (mph)	ROUNDED SSD FOR DESIGN [1] (ft)	CALCULATED *K* VALUE [2] $K = \frac{S^2}{(400 + 3.5S)}$	*K* VALUE ROUNDED FOR DESIGN
20	115	16.5	17
25	155	25.5	26
30	200	36.4	37
35	250	49.0	49
40	305	63.4	64
45	360	78.1	79
50	425	95.7	96
55	495	114.9	115
60	570	135.7	136
65	645	156.5	157
70	730	180.3	181

Notes:

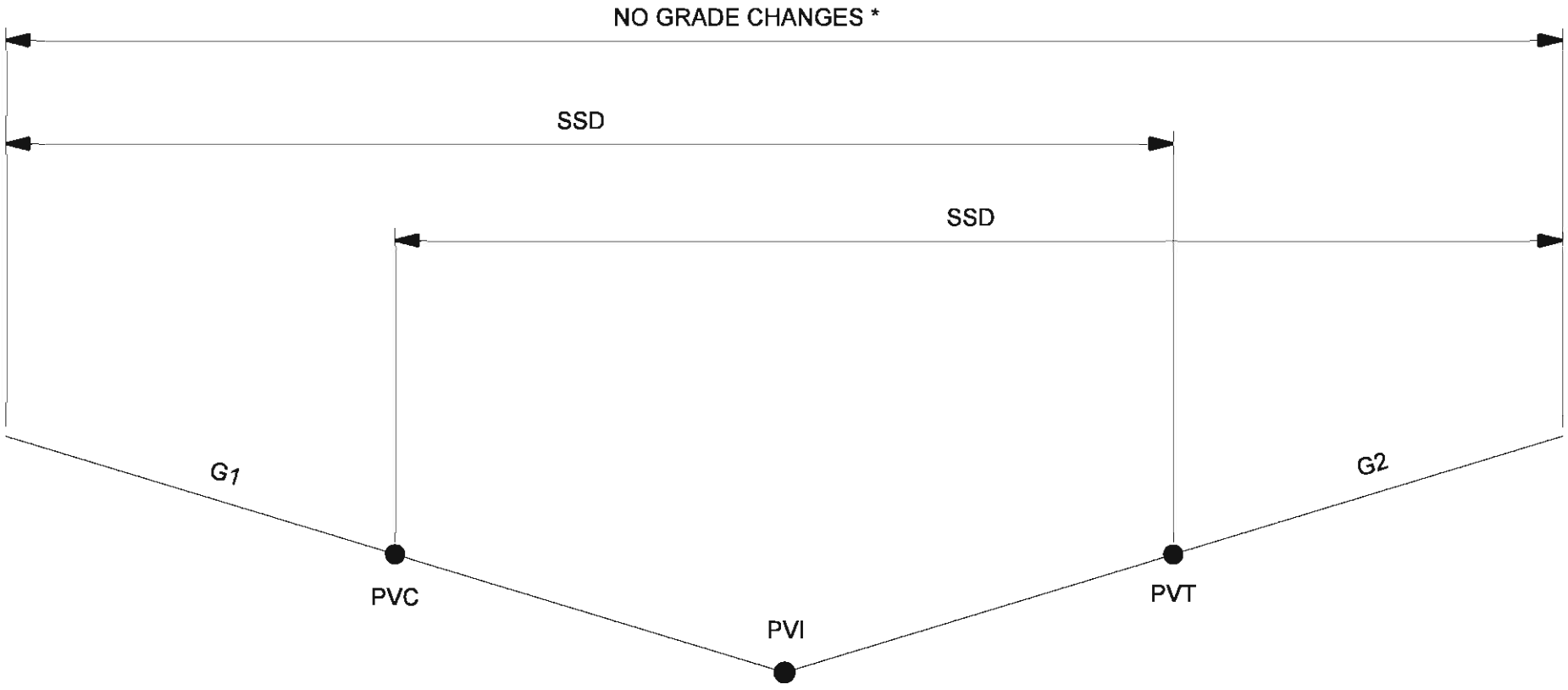
1. *Stopping sight distance (SSD) is from Figure 42-1A.*

2. *The K value is calculated using the rounded value for design stopping sight distance S and a headlight height of 2 ft.*

3. *If curbs are present and K > 167, proper drainage should be ensured near the low point of the curve.*

_K_ VALUE FOR SAG VERTICAL CURVE
(Stopping Sight Distance – Passenger Car)

Figure 44-3C



* No other vertical curves or angular breaks within this zone.

STOPPING SIGHT DISTANCE CHECK USING K-VALUES,
SAG VERTICAL CURVE

Figure 44-3C(1)

Design Speed (mph)	Avoidance Maneuver A (Stop on Rural Road)		Avoidance Maneuver B (Stop on Urban Road)		Avoidance Maneuver C (Speed/Path/ Direction Change on Rural Road)		Avoidance Maneuver D (Speed/Path/ Direction Change on Suburban Road)		Avoidance Maneuver E (Speed/Path/ Direction Change on Urban Road)	
	DSD (ft)	*K* Value	DSD (ft)	*K* Value	DSD (ft)	*K* Value	DSD (ft)	*K* Value	DSD (ft)	*K* Value
20	90	25	270	68	300	83	360	73	415	111
25	110	39	335	100	375	101	450	101	515	139
30	220	55	490	131	450	120	535	144	620	168
35	275	70	590	160	525	141	625	170	720	197
40	330	86	690	188	600	163	715	195	825	227
45	395	104	800	220	675	184	800	220	930	257
50	465	124	910	251	750	205	890	245	1030	285
55	535	144	1030	285	865	238	980	271	1135	315
60	610	166	1150	320	990	274	1125	312	1280	357
65	695	190	1275	355	1050	291	1220	340	1365	381

Notes:

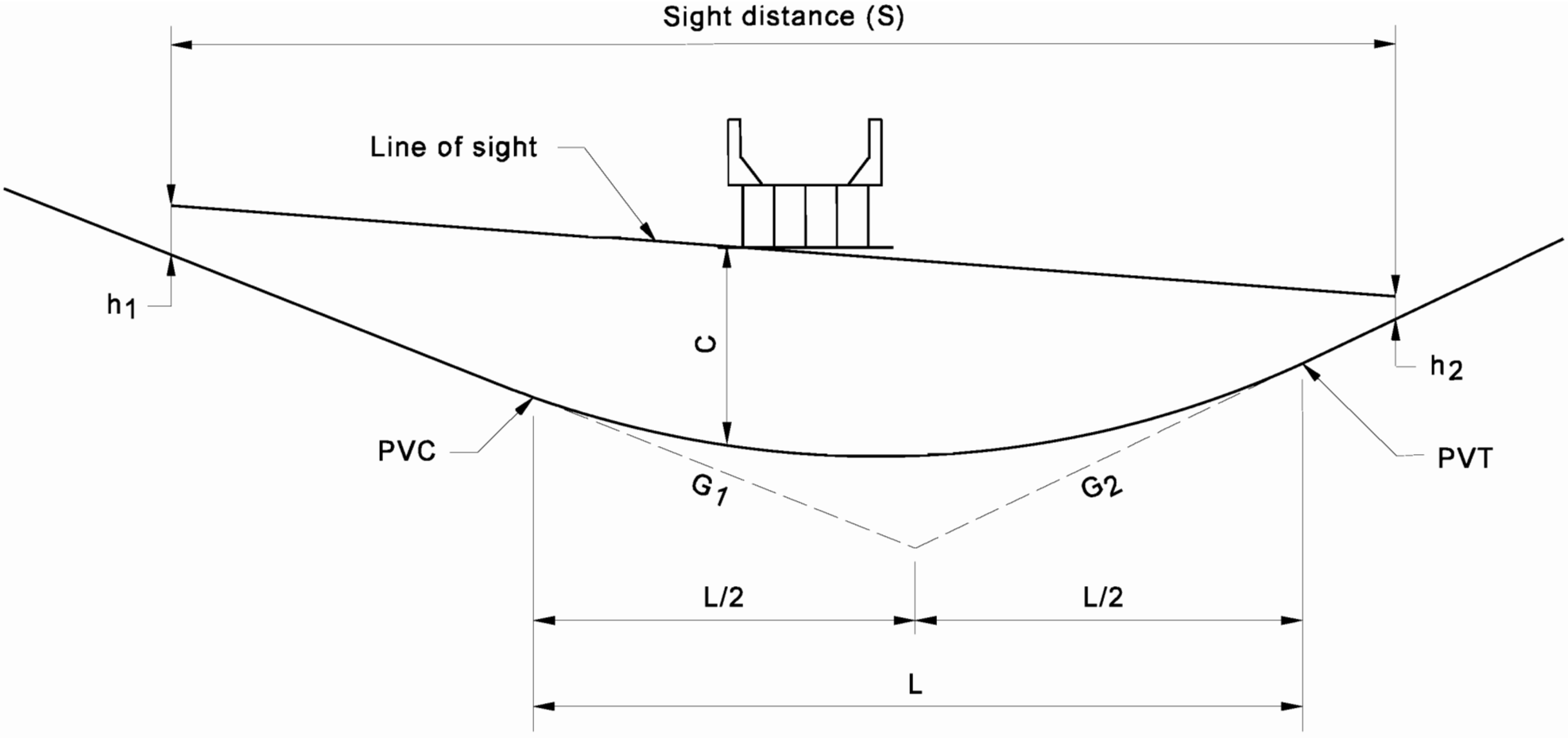
1. *The K value is calculated using the rounded value for design decision sight distance and headlight height of 2 ft.*

$$K = \frac{DSD}{120 + 3.5S}$$

2. *If curbs are present and K > 167, proper pavement drainage should be ensured near the low point of the curve.*

_K_ VALUE FOR SAG VERTICAL CURVE
(Decision Sight Distance – Passenger Car)

Figure 44-3D



SIGHT DISTANCE AT UNDERCROSSING

Figure 44-3D(1)

ELEMENT	ABBREVIATION	DEFINITION
Point of Vertical Curvature	PVC	The point at which a tangent grade ends and the vertical curve begins.
Point of Vertical Tangency	PVT	The point at which the vertical curve ends and the tangent grade begins.
Point of Vertical Intersection	PVI	The point where the extension of two tangent grades intersect.
Grade	G_1, G_2	The rate of slope between two adjacent PVIs expressed as a percent. The numerical value for percent of grade is the vertical rise or fall in feet for each 100 ft of horizontal distance. An upgrade in the direction of stationing is identified as plus (+). A downgrade is identified as minus (-).
External Distance	M	The vertical distance (offset) between the PVI and the roadway surface along the vertical curve.
Algebraic Difference in Grade	A	The value is the deflection in percent between two tangent grades.
Length of Vertical Curve	L	The horizontal distance in feet from the PVC to the PVT.

VERTICAL-CURVE DEFINITIONS

Figure 44-3E

M = Mid-ordinate, feet
Z = Any tangent offset, feet
L = Horizontal length of vertical curve, feet
X = Horizontal distance from PVC or PVT to any ordinate Z, feet
G_1 and G_2 = Rates of grade, expressed algebraically, percent

All expressions are to be calculated algebraically.

$$PVI\ Elev = PVC\ Elev + \frac{LG_1}{200}$$

$$PVT\ Elev = PVC\ Elev + \frac{L(G_1 + G_2)}{200}$$

$$M = \frac{L(G_2 - G_1)}{800}$$

For offset Z at distance X from PVC or PVT:

$$Z = M\left(\frac{2X}{L}\right)^2 \quad \text{or} \quad Z = \frac{X^2(G_2 - G_1)}{200L}$$

For slope S, in percent, of a line tangent to any point on the vertical curve at distance X measured from the PVC:

$$S = G_1 - \frac{X(G_1 - G_2)}{L}$$

Calculate location and elevation of the high or low point on the curve:

$$X_T = \frac{LG_1}{G_1 - G_2}$$

Where X_T equals the horizontal distance from the PVC to the high or low point on the curve, feet.

$$Elev = PVC\ Elev - \frac{L(G_1)^2}{200(G_2 - G_1)}$$

SYMMETRICAL VERTICAL-CURVE EQUATIONS

Figure 44-3F

Example 44-3.1

Given: G_1 = -1.75%
G_2 = +2.25%
Elev. of PVI = 577.50
Station of PVI = 13+80
L = 500 ft

Problem: Compute the grade for each 50-ft increment. Compute the low point station and elevation.

Solution:

1. Draw a diagram of the vertical curve and determine the station of the beginning (PVC) and the end (PVT) of the curve.

   Beginning Station (PVC) = PVI Sta. – 0.5L = (13+80) – (2+50) = 11+30
   End Station (PVT) = PVI Sta. + 0.5L = (13+80) + (2+50) = 16+30

2. Solve the vertical curve equations:

$$M = \frac{(G_2 - G_1)L}{800} = \frac{[2.25 - (-1.75)]\,500}{800} = 2.50\ ft$$

$$Z = M\left(\frac{X}{L/2}\right)^2 = \frac{4MX^2}{L^2} = \frac{(4)(2.5)X^2}{250{,}000} = \frac{X^2}{25000}$$

3. Set up a table to show the vertical curve elevations at the 50-ft increments:

Station	Inf.	Tangent Elevation	X	X^2	Z	Grade Elevation
11+30	PVC	581.875	0	0	0	581.875
11+80		581.000	50	2500	0.100	581.100
12+30		580.125	100	10000	0.400	581.525
12+80		579.250	150	22500	1.125	580.375
13+30		578.385	200	40000	2.000	580.375
13+80	PVI	577.500	250	62500	3.125	580.625
14+30		578.675	200	40000	2.000	580.675
14+80		579.750	150	22500	1.125	580.875
15+30		580.875	100	10000	0.400	581.275
15+80		582.000	50	2500	0.100	582.700
16+30	PVT	583.125	0	0	0	583.125

4. Determine low point on curve:

$$X_t = \frac{LG_1}{G_1 - G_2} = \frac{500(-1.75)}{-1.75 - 2.25} = \frac{-875}{-4.00} = 218.75\ ft\ \ from\ PVC$$

therefore, the station at low point is

(11+30.00) + (2+18.75) = (13+48.75)

and the elevation of low point on curve is

$$Elev.\,PVC - \frac{L(G_1)^2}{(G_2 - G_1)\,200} = 581.875 - \frac{500(-1.75)^2}{[2.25 - (-1.75)]\,200} = 581.875 - 1.545 = 580.33$$

VERTICAL-CURVE COMPUTATIONS
(Example 44-3.1)

Figure 44-3G

P = Theoretical Point at PVI
M = Offset from the PVI to the curve, feet
Z = Any tangent offset, feet
L = Horizontal length of vertical curve, feet
L_1 = Horizontal distance from PVC to PVI, feet
L_2 = Horizontal distance from PVT to PVI, feet
X = Horizontal distance from PVC or PVT to any ordinate Z, feet
G_1 and G_2 = Rates of grade, expressed algebraically, percent

All expressions to be calculated algebraically, as follows:

$$PVI\ ELEV = PVC\ ELEV + \frac{G_1 L_1}{100}$$

$$PVT\ ELEV = PVC\ ELEV + \frac{G_1 L_1}{100} + \frac{G_2 L_2}{100}$$

$$P\ ELEV = PVC\ ELEV + \frac{L_1}{L}\left(\frac{G_1 L_1 + G_2 L_2}{100}\right)$$

$$M = \left(\frac{L_1 L_2}{200\ L}\right)(G_2 - G_1) = \frac{P\ ELEV - PVI\ ELEV}{2}$$

For offset Z at distance X from PVC:

$$Z = M\left(\frac{X}{L_1}\right)^2$$

For offset Z at a distance X from PVT:

$$Z = M\left(\frac{X}{L_2}\right)^2$$

The high or low point on curve is calculated as follows:

If the high or low point occurs on the left portion of the curve:

$$X_T = \frac{L_1}{L_2}\left(\frac{G_1\ L}{(G_1 - G_2)}\right)$$

Where X_T equals the horizontal distance from the PVC to the high or low point on the curve, feet.

$$Elev\,of\ this\,Pt. = PVC\ ELEV - \frac{L_1}{L_2}\left[\frac{L(G_1)^2}{(G_2 - G_1)200}\right]$$

If the high or low point occurs on the right portion of curve:

$$X_T = \frac{L_2}{L_1}\left(\frac{G_2\ L}{(G_2 - G_1)}\right)$$

Where X_T equals the horizontal distance from the PVC to the high or low point on the curve, feet.

$$Elev\,of\ this\,Pt. = PVT\ ELEV - \frac{L_2}{L_1}\left[\frac{L(G_2)^2}{(G_1 - G_2)200}\right]$$

UNSYMMETRICAL VERTICAL-CURVE EQUATIONS

Figure 44-3H

TO PASS A VERTICAL CURVE THROUGH A GIVEN POINT P

G_1	=	Grade In, %
G_2	=	Grade Out, %
A	=	Algebraic difference in grades, %
Z	=	Vertical curve correction at point P, feet
X	=	Distance from point P to PVC, feet
D	=	Distance from point P to PVI, feet
L	=	Length of vertical curve, feet

Given: G_1, G_2, D

Find: Length of vertical curve

Solution:

1. Find algebraic difference in grades:

$$A = G_2 - G_1$$

2. Find vertical curve correction at point P at distance *x* measured from PVC:

$$Z = X^2 \left(\frac{G_2 - G_1}{200\,L} \right)$$

3. From inspection of the above diagram:

$$\frac{L}{2} = X + D \text{, or } L = 2(X + D)$$

Substituting $2(X+D)$ for L and A for (G_2-G_1) yields:

$$AX^2 = (-400ZX) + (-400DZ) = 0$$

4. Solve for X given the quadratic equation as follows:

$$X = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a} = \frac{400Z \pm \sqrt{160{,}000\,Z^2 + 1600\,ADZ}}{2A}$$

Solving for X will result in two answers. If both answers are positive, there are two solutions. If one answer is negative, it can be eliminated and only one solution exists.

5. Substitute X and D into the equation shown in Step 3 and solve for L.

Note: Two positive X values will result in two solutions for L. Desirably, the solution that results in a longer L should be used provided that it satisfies the stopping sight distance criteria based on the selected design speed and algebraic difference in grades. See Figures 44-3A and 44-3C).

VERTICAL-CURVE COMPUTATIONS

Figure 44-3I

Example 44-3.2

Given: Design Speed = 55 mph
G_1 = -1.5%
G_2 = +2.0%
A = 3.5%
PVI Station = 49+10
PVI elevation = 642.10

Problem: At Station 47+46, 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 ft in depth, 20 ft in width and at right angles to the highway. What would be the length of the vertical curve that would provide a 16.5-ft clearance under the railroad bridge?

Solution:

1. Sketch the problem with known information.

Example 44-3.2 (continued)

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

   From inspection of the sketch, the critical location is on the left side of the railroad bridge. The critical station is as follows:

   Sta. P = Bridge Centerline Sta. – ½ (Bridge Width)
   Sta. P = Sta. (47+46) – ½ (0+20)
   Sta. P = Sta. 47+36

3. Determine the elevation of Point P:

   Elev. P = Elev. Top of Bridge – Bridge Depth – Clearance
   Elev. P = 669.00 – 4.00 – 16.5
   Elev. P = 648.50

4. Determine distance *D* from Point P to PVI:

   D = STA. PVI – STA. P
   = (49+10) – (47+36) = 174 ft

5. Determine the tangent elevation at Point P:

$$Elev = PVI\ Elev - G_1\left(\frac{D}{100}\right)$$

$$Elev = 642.10 - (-1.5)\left(\frac{174}{100}\right)$$

   Elev. is 644.71

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

   Z = Elev. on Curve – Elev. on Tangent

   = 648.50 – 644.71 = 3.79 ft

7. Solve for *X* using equation from Figure 44-3 I, Step 4:

$$X = \frac{400\,Z \pm \sqrt{160{,}000\,Z^2 + 1600\,ADZ}}{2A}$$

$$X = \frac{400\,(3.79) \pm \sqrt{(160{,}000)(3.79)^2 + 1600(3.5)(174)(3.79)}}{2(3.5)}$$

8. Using Figure 44-3 I, Step 3, solve for *L*:

X = 566.24 ft or -133.10 ft [Disregard negative value]

$L = 2(X + D)$
$L = 2(566.24 + 174)$
$\underline{L}$ = 1480.48 ft

9. Determine if the solution meets the stopping sight distance for the 55-mph design speed. From Figure 44-3C, the K value is 115.

The algebraic difference in grades is as follows:

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

From Equation 44-3.2, the minimum length of vertical curve which meets the stopping sight distance is as follows:

$L = KA$
$= (115)(3.5)$
$= 402.50$ ft

L of 1480.48 ft exceeds 402.50 ft., therefore the desirable stopping sight distance is satisfactory.

VERTICAL-CURVE COMPUTATIONS
(Example 44.3-2)

Figure 44-3J

Type	Minimum Clearance (ft-in.)
Freeway Under Bridge	16’-6” (1.) (2.)
Arterial Under Bridge	16’-6” (1.) (3.)
Collector Under Bridge	14’-6” (1.)
Local Road Under Bridge	14’-6” (1.)
Roadway under Pedestrian Bridge	17’-6” (1.)
Roadway under Traffic Signal	17’-0” (1.) (4.)
Railroad under Roadway (Typical)	23’-0” (5.)
Roadway under Sign Truss	17’-6” (1.)

Notes:

1. *Value allows 6 in. for future resurfacing.*

2. *A 14’-6” clearance (including future resurfacing) may be used in an urban area where an alternative freeway facility with a 16’-0” clearance is available.*

3. *In a highly urbanized area, a minimum clearance of 14’-6” (including future resurfacing) may be provided if there is at least one route with a 16’-0” clearance.*

4. *Distance is measured from roadway surface to the bottom of signal at the bottom of the back plate or to the mast arm. See the INDOT* Standard Drawings.

5. *See Chapter Sixty-nine for additional information on a railroad under a roadway.*

MINIMUM VERTICAL CLEARANCE
(New Construction or Reconstruction)

Figure 44-4A