IOWA DOT

Office of Design

2B-1

Vertical Alignment

Design Manual
Chapter 2
Alignments

Originally Issued: 09-22-00
Revised: 07-02-15

This section addresses the following:

- Vertical grades,
- Vertical curves,
- Passing Opportunity Considerations, and
- Plan curve data.

> ***Quick Tips:***
>
> - A formal design exception is required for a vertical grade value that is below the values highlighted in yellow in the criteria tables from Section 1C-1.
> - Vertical curves influence stopping sight distance. A formal design exception is required for a vertical curve that does not provide at least the acceptable stopping sight distance highlighted in yellow in the criteria tables from Section 1C-1.
> - Refer to Section 6D-1 for criteria on measuring sight distance on vertical curves.

Vertical Grades

Maximum Grade

Values for maximum vertical grades listed in the design criteria tables from Section 1C-1 are based on the AASHTO Greenbook criteria for rolling terrain.

Minimum Grade

Values for minimum vertical grades listed in the design criteria tables from Section 1C-1 are based on surface drainage. The cross-slope of the pavement surface is usually adequate to drain laterally. The vertical grade drains the pavement surface longitudinally.

Minimum Grade on Curbed Roadways

Roadways with curbs need a grade of at least 0.3% to drain longitudinally to inlets.

Minimum Grade on Roadways with Shoulders

Flat grades (0%) are usually adequate to drain the pavement surface for roadways with shoulders since the pavement cross-slope drains the water off of the roadway. Flat grades will create flat areas on the pavement surface in areas of superelevation transition. The grade through superelevation transition should drain the pavement since the cross-slope will not drain water off of the surface. Refer to Section 2A-4 for superelevation and pavement drainage considerations.

Minimum Grade on Bridges

For rural bridge replacement projects, the existing grade of the approach may be flatter than the preferred 0.5% minimum listed in the criteria tables from Section 1C-1. Updating these grades to 0.5% may need several hundred feet of reconstruction while providing only minimal benefit. Use the following criteria for rural bridge replacement projects with approaches less than a 0.5% grade:

- Maintain the existing grade for bridges less than 250 feet long when the new shoulder width is equal to or greater than 10 feet.
- Maintain the existing grade for bridges less than 250 feet long with 8 foot shoulders and an open barrier rail system.

For bridge lengths greater than 250 feet, or when shoulder widths are less than or equal to 8 feet without an open barrier rail, the approaching grade will need to be corrected to at least a 0.5%

minimum or be evaluated to make sure water does not encroach upon the traveled part of the roadway.

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 combination of the gradient and length of the grade will determine the truck speed reduction. A reasonable reduction in speed is less than 10 mph.

Designers can use Figure 1 when designing Interstates, Freeways, and Expressways to estimate the speed reduction for a loaded truck with an entering speed of 70 mph.

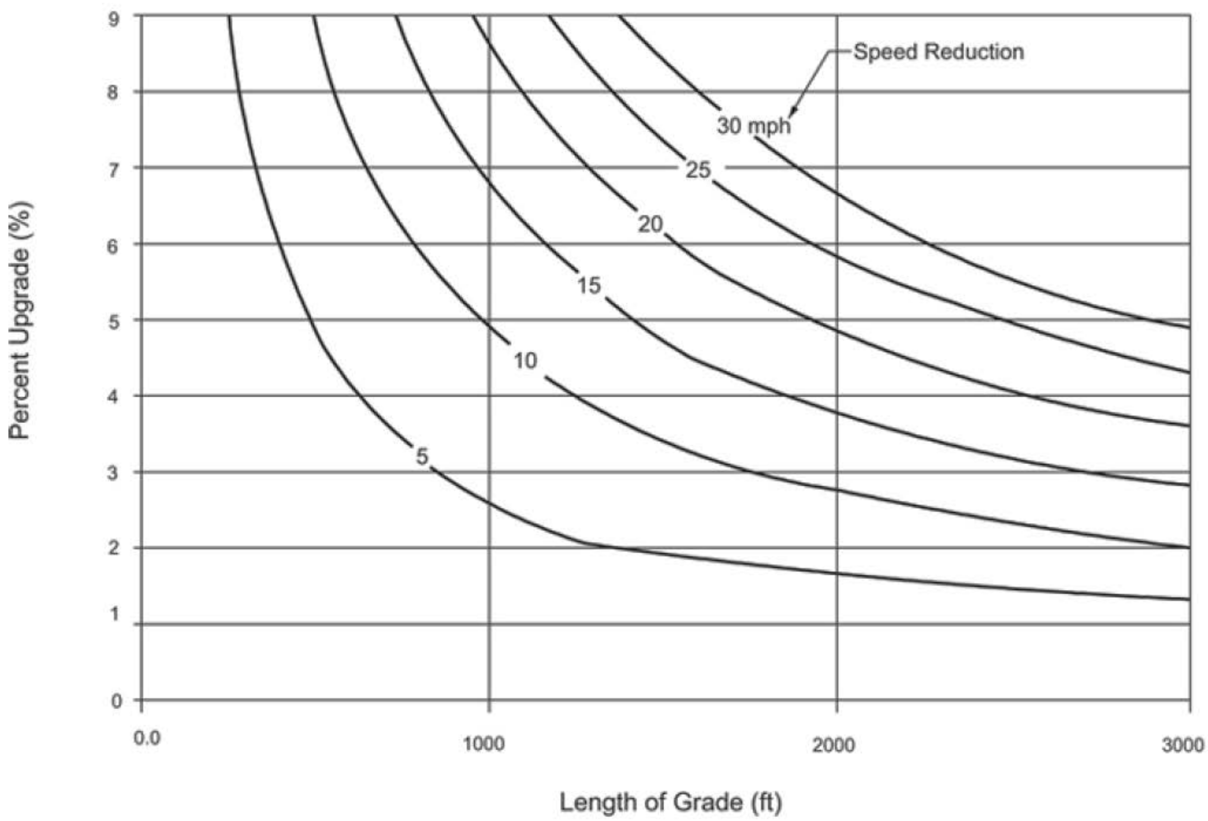

Figure 1: Critical length of grade for design (Reference: Figure 3-28 AASHTO Greenbook, 2011).

Vertical Curves

Use vertical curves to smooth changes in vertical direction. A crest curve occurs when the arc of the curve is below the VPI. A sag curve occurs when the arc is above the VPI. Typically, vertical curves are symmetrical. This means the tangent length from VPC to VPI equals the tangent length from VPI to VPT. Figure 2 illustrates the components of a vertical curve.

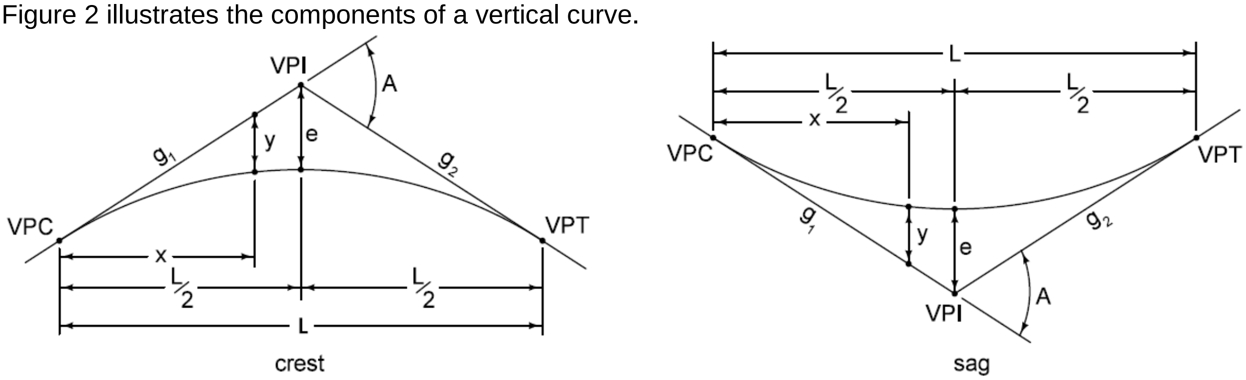

Figure 2: Illustrations of a crest and sag vertical curve.

Vertical Curve Components

Defined below are the components that apply to crest and sag vertical curves.

A = Algebraic difference in gradients, $g_2 - g_1$.

> **Note:** g_1 and g_2 are gradients, or tangent grades, of a slope given in percent. These gradients are determined by dividing the difference in elevation of two points by the horizontal distance between them and then multiplying by 100.

L = Total length of vertical curve.

K = Rate of vertical curvature.

VPC = Vertical Point of Curvature.

VPT = Vertical Point of Tangency.

VPI = Vertical Point of Intersection.

x = Horizontal distance to any point on the curve from the VPC.

x_t = Turning point, which is the minimum or maximum point of the curve.

e = Vertical offset or middle ordinate, which is the vertical distance from the VPI to the arc.

y = Vertical distance at any point on the curve to the tangent grade.

r = Rate of change of grade.

E_{VPC} = Elevation of VPC.

E_{VPT} = Elevation of VPT.

E_x = Elevation of a point on the curve at a distance x from the VPC.

E_t = Elevation of the turning point.

Formulas

The formulas below are used in the design of vertical curves.

$A = g_2 - g_1$	g_1 and g_2 are in percent
$K = \frac{L}{A}$	L is given in feet and g_1 and g_2 are in percent
$r = \frac{A}{100L}$	L is given in feet and g_1 and g_2 are in percent
$e = \frac{AL}{800}$	L is given in feet
$y = \frac{4ex^2}{L^2} = \frac{1}{2}rx^2 = \frac{Ax^2}{200L}$	measured from the tangent that passes through VPC and VPI: L and x are given in feet
$E_x = E_{VPC} + g_1x + \frac{1}{2}rx^2$	L and x are given in feet: convert g_1 to a decimal
$x_t = -\frac{g_1}{r}$	x_t is in feet: convert g_1 to a decimal
$E_t = E_{VPC} - \frac{g_1^2}{2r}$	convert g_1 to a decimal

Design Considerations

Several items to consider in the process of designing a vertical curve are:

Sight Distance

The principal control in the design of a vertical curve is stopping sight distance. Stopping sight distance is required throughout an alignment. Rate of vertical curvature (K) is a design control to measure stopping sight distance. Refer to Section 6D-1 for rate of vertical curvature criteria.

Decision sight distance is desirable to decision points on a roadway. Crest vertical curves influence the available decision sight along a roadway. Refer to Section 6D-1 for decision sight distance criteria.

Pavement Surface Drainage

Pavement surface drainage should be considered in the design of a vertical curve. A rate of vertical curvature greater than 167 may cause pavement surface drainage problems, especially near the high point of a crest curve or low point of sag curve. Designers should check pavement surface drainage near the turning points of vertical curves to make sure the pavement surface drains. The evaluation should confirm the cross-slope of the pavement drains the pavement surface.

For curbed roadways, the longitudinal grade drains water to the inlets.

Combination of Horizontal and Vertical Alignment

Horizontal and vertical alignments should be designed together to provide stopping and decision sight distance.

Poor coordination between superelevation transition and a vertical alignment may result in a flat spot in the pavement surface, which will not drain water off the surface. Refer to Section 2A-4 for more information about the coordination between superelevation transition and vertical alignment.

Coordination with Bridge Design

Avoid sag vertical curves which result in a low point on a bridge. Adjust the vertical alignment to move the low point off the bridge.

Bridge Clearances

Profiles must be designed to provide adequate bridge clearances. Refer to Section 1C-1 for clearance criteria.

Snow Concerns

In areas of flat open ground, a vertical alignment 3 to 5 feet above natural ground can reduce snow drifting. A vertical alignment 3 feet above the natural provides a 5 foot standard ditch depth.

Conveying Drainage underneath Roads

Locate profiles such that:

- Culverts do not extend into the subgrade, and preferably not into the subgrade treatment.
- Adequate headwater is provided for culvert design.

Profiles for bridges over streams or rivers need to accommodate bridge structure, design flows, and freeboard. Coordinate with Preliminary Bridge Design.

Earthwork

The vertical alignment should desirably balance the earthwork, but this should not be achieved at the cost of providing stopping and decision sight requirements through vertical curves.

Minimum Vertical Curve Length

A minimum curve length (in feet) of three times the design speed is the minimum length for both sag and crest vertical curves. Curve lengths based upon a minimum K value for small values of algebraic differences in grade (A) result in small curve lengths or no curve length at all because the sight line passes over the high point. Short curves or no curve is not a desirable practice; therefore, the minimum length of curve based upon a design is the desirable practice.

Passing Opportunity Considerations

The level of service of a two way, two lane roadway is directly impacted by the percentage of the roadway that provides adequate sight distance to safely pass a slower moving vehicle. Designers should provide frequent passing opportunities for drivers. No table for a minimum number of passing opportunities per given distance for different design situations exists; however, procedures presented in the Highway Capacity Manual provide an evaluation of the level of service based on passing opportunities and vehicle volume and mix. Providing frequent passing opportunities becomes increasingly more important as traffic volumes increase. If ample passing opportunities cannot be provided the designer may want to consider alternative alignments or providing passing lanes.

Plan Curve Data

The common vertical alignment design values and degree of accuracy shown on the plans include:

- VPI Stationing – Placed at nearest 25 foot increment (e.g., 125+25.00 or 125+50.00).
- Length of curves – 50 foot increments.
- Grades – Nearest 0.01% and preferably divisible by 4.
- K – To the nearest whole number.
- Elevation – to the 0.01 foot.

Display vertical curve data in the following order on plan sheets:

VPI
Elv
Len
K

Chronology of Changes to Design Manual Section:

002B-001 Vertical Alignment

7/2/2015	Revised	
	Added in information regarding passing opportunity considerations.	
7/22/2014	Revised	
	Change title to Vertical Alignment. Added in information for vertical grades. Changed "Definitions" to "Vertical Curve Components". Expanded on Design Considerations and Plan Curve Data.	
1/15/2014	Revised	
	Section 6D-5 has been voided. Reference Section 6D-1.	
4/17/2012	Revised	
	Removed word 'Spiral' from Plan Curve Data Section. Added hyperlinks.	
5/28/2010	Revised	
	Added language about moving the low point of a vertical curve off of a bridge.	