Section 4

ELEMENTS OF DESIGN

Sight Distance and Vertical Alignment

EPG Category 230: Geometrics

230: Alignments of the Roadways

230.2: Vertical Alignment

AASHTO Green Book Chapter 3

Elements of Design: Sight Distance

EPG Category 230.2: Vertical Alignment

Definition – Sight distance is the length of roadway visible ahead to the driver of the vehicle.

Types of Sight Distances

- Stopping Sight Distance (SSD)
- Decision Sight Distance (DSD)
- Passing Sight Distance (PSD)
- Operational Sight Distance (OSD)

Elements of Design: Sight Distance

EPG Category 230.1: Horizontal Alignment

Stopping Sight Distance (SSD) refers to both horizontal and vertical views.

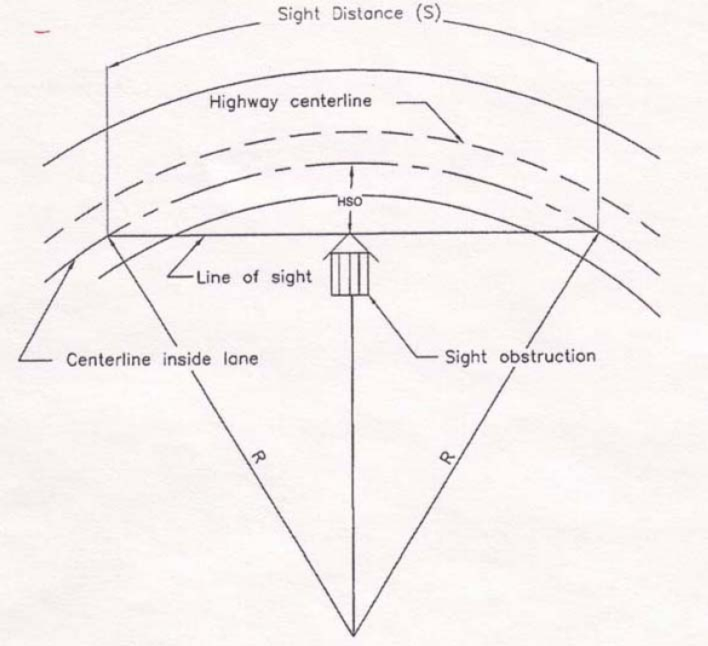
$$HSO = R\left[\left(1 - \cos \frac{28.65S}{R}\right)\right]$$

Where,

HSO= Horizontal sightline offset (ft)

R= Radius of Curve (ft)

S= Stopping Sight Distance (ft)



Elements of Design: Sight Distance

EPG Category 230.2: Vertical Alignment

Vertical SSD

By definition, SSD is the sum of two distances

1. *Break reaction distance:* the distance traversed by the vehicle during the time the driver takes to react.
2. *Breaking distance:* the distance needed to actually stop the vehicle.

Elements of Design: Sight Distance

EPG Category 230.2: Vertical Alignment

Decision Sight Distance

Decision sight distance is used when SSD is just not adequate to allow a reasonably competent driver the distance to react to potentially hazardous situations. If a situation that requires DSD arises, consult the AASHTO Green Book.

Operational Sight Distance

Operational Sight Distance is not a design consideration for divided lane highways. OSD is based on the 85^{th} percentile speed at which 85% of traffic travels at or less.

This speed is generally determined from speed studies made on a roadway after it has been opened to traffic.

Elements of Design: Sight Distance

EPG Category 230.2: Vertical Alignment

Passing Sight Distance

Passing sight distance is only a consideration for undivided highways. It is not practical nor desirable to design crest vertical curves based on PSD because of the excessive length of curves required.

So, how do we get adequate PSD?

To obtain adequate PSD and still keep the length of curves to an acceptable length, vertical curves should be designed based on appropriate grades for the design speed and terrain.

However, if PSD needs to be calculated to determine the "no passing zone" striping. The AASHTO Green Book has formulas and tables to determine design passing sight distance in chapter 3.

Elements of Design: Sight Distance

EPG Category 230.2: Vertical Alignment

Passing Sight Distance

Assumptions for calculating minimum PSD:

1. The overtaken vehicle travels at uniform speed.

2. The passing vehicle has reduced speed and trails the overtaken vehicle as it enters a passing section.

3. When the passing section is reached, the passing driver needs a short period of time to perceive the clear passing section and to react to start his/her maneuvers.

4. Passing is accomplished under what may be termed a delayed start and a hurried return in the face of opposing traffic. The passing vehicle accelerates during the maneuver, and its avg. speed while passing is 10 mph higher than that of the overtaken vehicle.

5. When passing vehicle returns to its lane, there is a suitable clearance length between it and an oncoming vehicle in the other lane.

Elements of Design: Sight Distance

EPG Category 230.2: Vertical Alignment

Passing Sight Distance

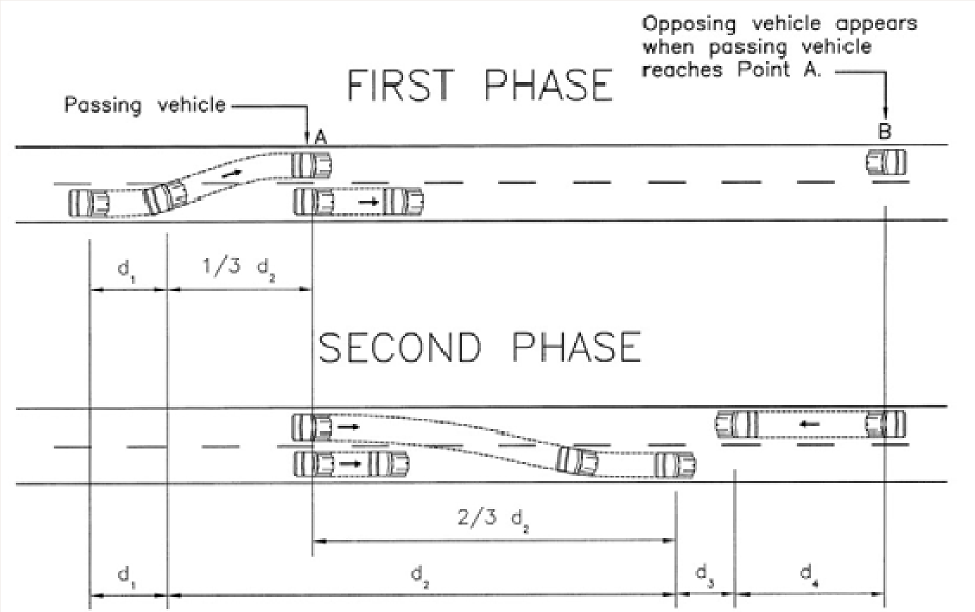
The minimum passing sight distance for 2-lane highways is determined as the sum of the following four distances:

d_1 – perception and reaction distance.

d_2 – distanced traveled while passing on the left lane.

d_3 – distance between the passing vehicle at the end of maneuver and the opposing vehicle.

d_4 – 2/3 d_2



Elements of Passing Sight Distance for 2-Lane Highways (Green Book)

Elements of Design: Sight Distance

EPG Category 230.2: Vertical Alignment

Passing Sight Distance

Component of passing maneuver	Metric				US Customary			
	Speed range (km/h)				Speed range (mph)			
	50-65	66-80	81-95	96-110	30-40	40-50	50-60	60-70
	Average passing speed (km/h)				Average passing speed (mph)			
	56.2	70.0	84.5	99.8	34.9	43.8	52.6	62.0
Initial maneuver:								
a = average acceleration[a]	2.25	2.30	2.37	2.41	1.40	1.43	1.47	1.50
t_1 = time (sec)[a]	3.6	4.0	4.3	4.5	3.6	4.0	4.3	4.5
d_1 = distance traveled	45	66	89	113	145	216	289	366
Occupation of left lane:								
t_2 = time (sec)[a]	9.3	10.0	10.7	11.3	9.3	10.0	10.7	11.3
d_2 = distance traveled	145	195	251	314	477	643	827	1030
Clearance length:								
d_3 = distance traveled[a]	30	55	75	90	100	180	250	300
Opposing vehicle:								
d_4 = distance traveled	97	130	168	209	318	429	552	687
Total distance, $d_1 + d_2 + d_3 + d_4$	317	446	583	726	1040	1468	1918	2383

[a] For consistent speed relation, observed values adjusted slightly.

Note: In the metric portion of the table, speed values are in km/h, acceleration rates in km/h/s, and distances are in meters. In the U.S. customary portion of the table, speed values are in mph, acceleration rates in mph/sec, and distances are in feet.

Exhibit 3-5. Elements of Safe Passing Sight Distance for Design of Two-Lane Highways

Elements of Design: Sight Distance

EPG Category 230.2: Vertical Alignment

Passing Sight Distance

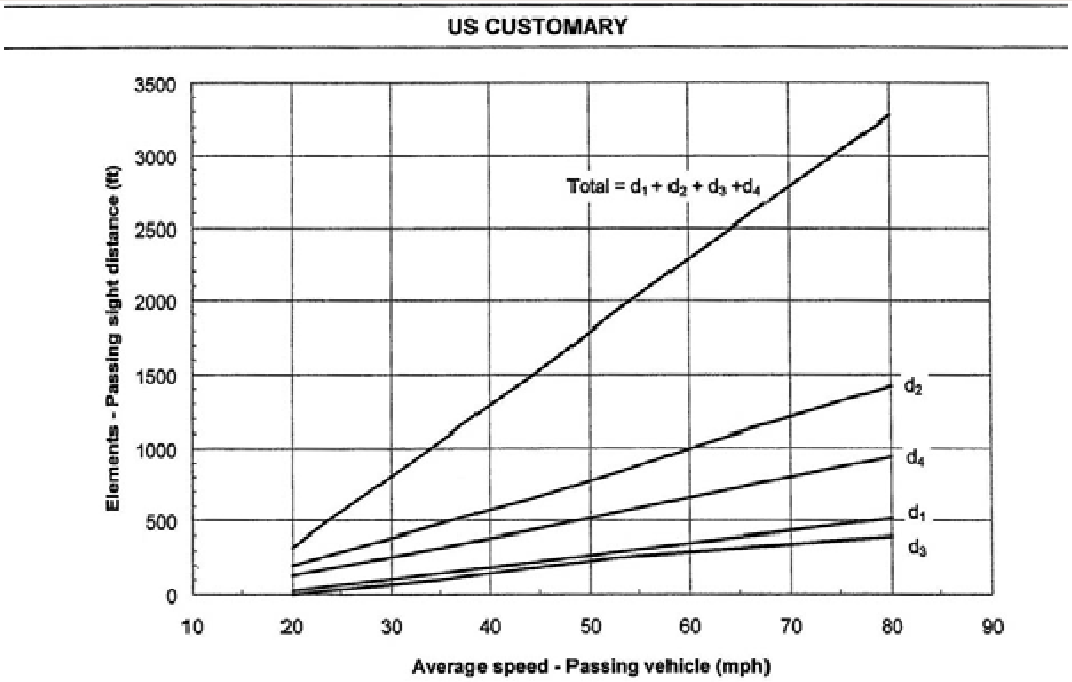


Exhibit 3-6. Total Passing Sight Distance and Its Components—Two-Lane Highways

Elements of Design: Sight Distance

EPG Category 230.2: Vertical Alignment

Passing Sight Distance

Metric					US Customary				
Design speed (km/h)	Assumed speeds (km/h)		Passing sight distance (m)		Design speed (mph)	Assumed speeds (mph)		Passing sight distance (ft)	
	Passed vehicle	Passing vehicle	From Exhibit 3-6	Rounded for design		Passed vehicle	Passing vehicle	From Exhibit 3-6	Rounded for design
30	29	44	200	200	20	18	28	706	710
40	36	51	266	270	25	22	32	897	900
50	44	59	341	345	30	26	36	1088	1090
60	51	66	407	410	35	30	40	1279	1280
70	59	74	482	485	40	34	44	1470	1470
80	65	80	538	540	45	37	47	1625	1625
90	73	88	613	615	50	41	51	1832	1835
100	79	94	670	670	55	44	54	1984	1985
110	85	100	727	730	60	47	57	2133	2135
120	90	105	774	775	65	50	60	2281	2285
130	94	109	812	815	70	54	64	2479	2480
					75	56	66	2578	2580
					80	58	68	2677	2680

Exhibit 3-7. Passing Sight Distance for Design of Two-Lane Highways

Elements of Design: Sight Distance

EPG Category 230.2: Vertical Alignment

Passing Sight Distance

Frequency of Passing Sections

It’s not practical to directly specify the frequency of passing sight distance areas. The designer should provide passing sight distance based on topography of the terrain, design speed, cost and spacing of entrances.

Passing Lanes and 2+1 roadways

In some situations, it may be more practical to provide dedicated passing opportunities by adding a climbing/passing lanes. For more complex situations, a designer should consider a 2+1 roadway. These facilities provide a continuous third lane to offer alternating passing opportunity to either direction of travel.

Contact the Engineering Policy Group for policy guidance.

Elements of Design: Vertical Alignment

EPG Category 230.2: Vertical Alignment

What is it?

Vertical alignment is a series of straight profile lines connected by vertical parabolic curves, and is referred as the "profile grade line" or PGL.

This PGL is based on the already established horizontal alignment.

Increasing PGL's = + grades

Decreasing PGL's = - grades

Elements of Design: Vertical Alignment

EPG Category 230.2: Vertical Alignment

Why is it important?

Vertical Alignment helps in the calculations of the amounts of cut and fill.

PGL is a key factor for proper drainage. In rock or in flood areas, the PGL should be higher than existing ground.

PGL sets the smoothness for the roadway. Drivers should feel comfortable when "riding" the roadway.

How do we determine vertical alignment?

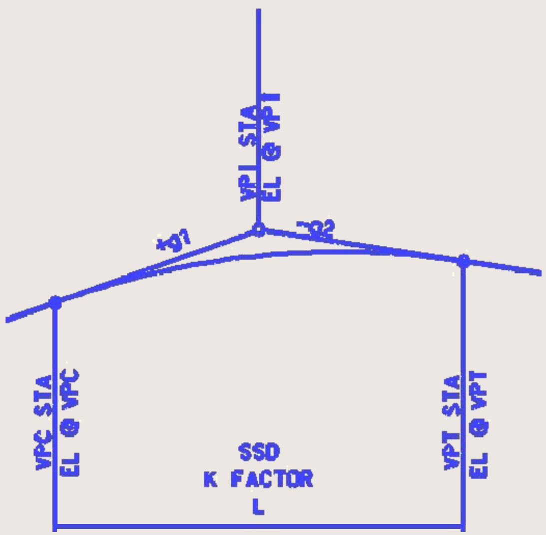
Vertical alignment is applied at the "design chain" trying to balance the hills and valleys so the beginning earthwork is close to balancing out. Please note that although the vertical alignment is well balanced, your earthwork may not be. Individual cross sections are used to accurately balance earthwork.

Elements of Design: Vertical Alignment

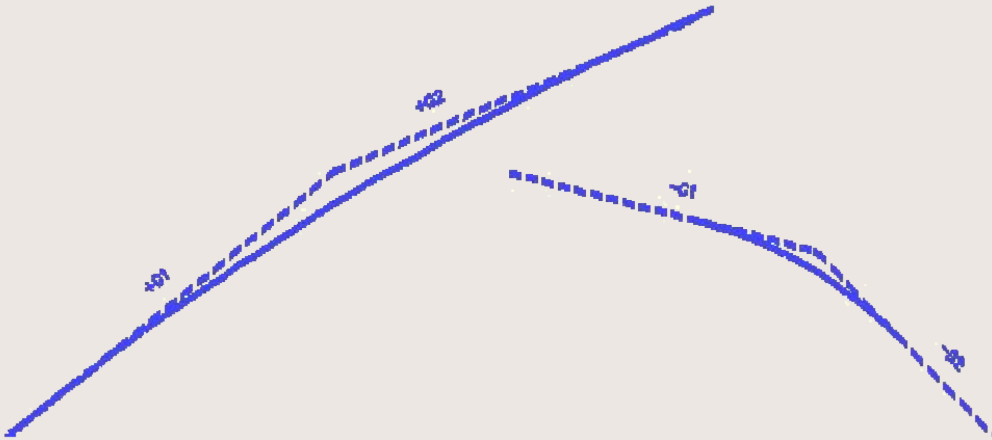
EPG Category 230.2: Vertical Alignment

Vertical Curve Geometry

Crest Curves



Type I



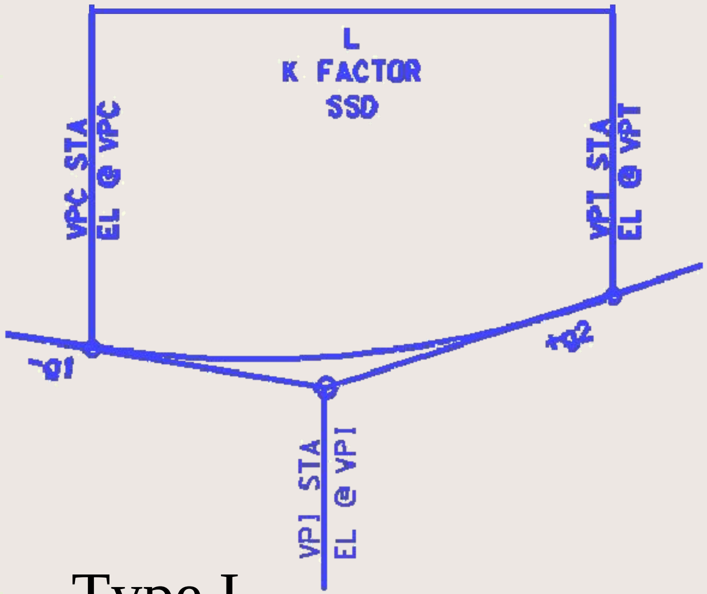
Type II

Elements of Design: Vertical Alignment

EPG Category 230.2: Vertical Alignment

Vertical Curve Geometry

Sag Curves



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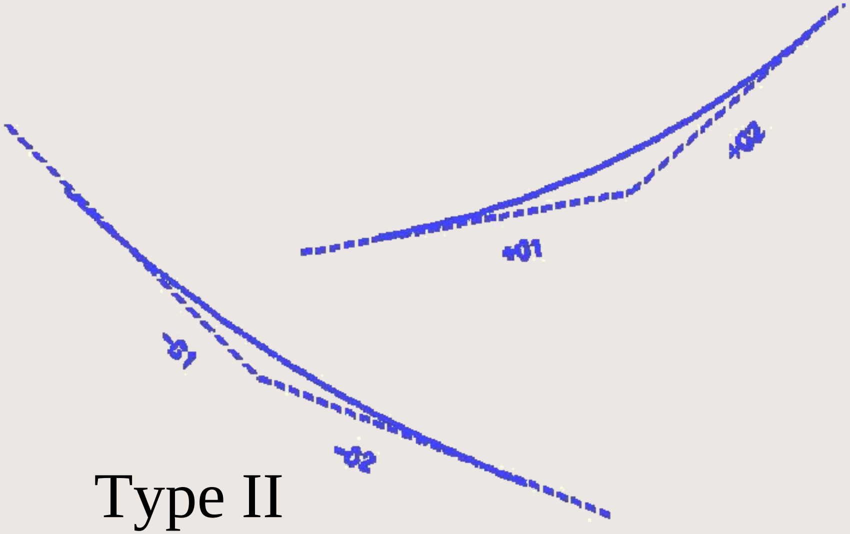
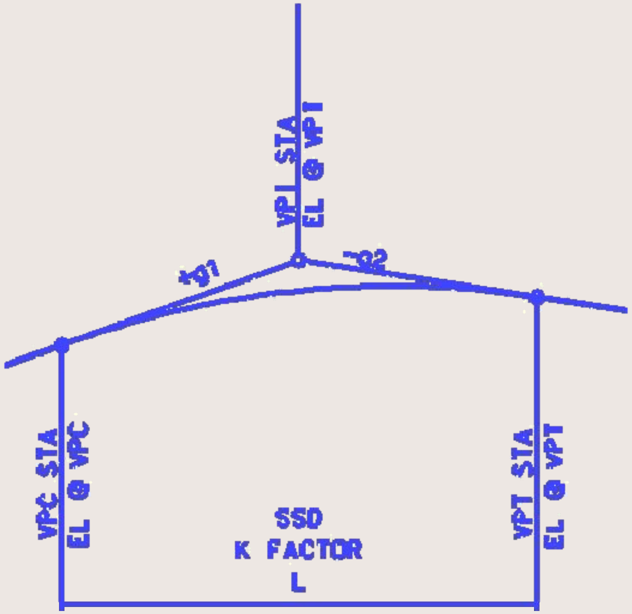


Type II

Elements of Design: Vertical Alignment

Vertical Alignment Geometry

VPI	Vertical Point of Intersection
VPC	Vertical Point of Curvature
VPT	Vertical Point of Tangency
g_1	Grade of Initial Tangent in Percent
g_2	Grade of Final Tangent in Percent
L	Length of Vertical Curvature
K	Vertical Curve Length Coefficient
x	Distance to Point on Curve, from VPC
E_x	Elevation of point on curve x from VPC
x_m	Location of min/max point on curve from VPC



Equations

$K = L / |g_1 - g_2|$

$E_x = E_{PC} + g_1 x/100 + x^2/200K$

$x_m = g_1 L / (g_2 - g_1)$**

(-)value = a low point,
(+)value = a high point

VPT Station = VPC station + L

VPI Station = VPC station + L/2

VPI Elevation = VPC Elev + (g1/100)(L/2)

OR

VPI Elevation = VPT Elev – (g2/100)(L/2)

**This equation only works for type I crest and sag vertical curves

Elements of Design: Vertical Alignment

EPG Category 230.2: Vertical Alignment

Calculating Vertical Curve Lengths

Crest curve lengths are based on SSD.

Sag curve lengths are based on: headlight sight distance, passenger comfort, drainage control and general appearance.

AASHTO Green Book shows the controls, equations and graphs to assist in determining SSD for either crest or sag curves.

There are three ways to calculate SSD:

1. Using equations.
2. Using graphs.
3. Using tables.

Elements of Design: SSD & Vertical Alignment

EPG Category 230.2: Vertical Alignment

Calculating length of vertical curves based on stopping sight distance using equations.

When $S < L$, $L = \dfrac{AS^2}{100(\sqrt{2h_1} + \sqrt{2h_2})^2}$

$h_1 = 3.5$ ft

$h_2 = 2.0$ ft

$L = AS^2/2158$

When $S > L$, $L = 2S - \dfrac{200(\sqrt{2h_1} + \sqrt{2h_2})^2}{A}$

$L = 2S – (2158/A)$

L=Length of Vertical Curve (ft)

S=Sight Distance (ft)

A=Algebraic difference in grades, percent

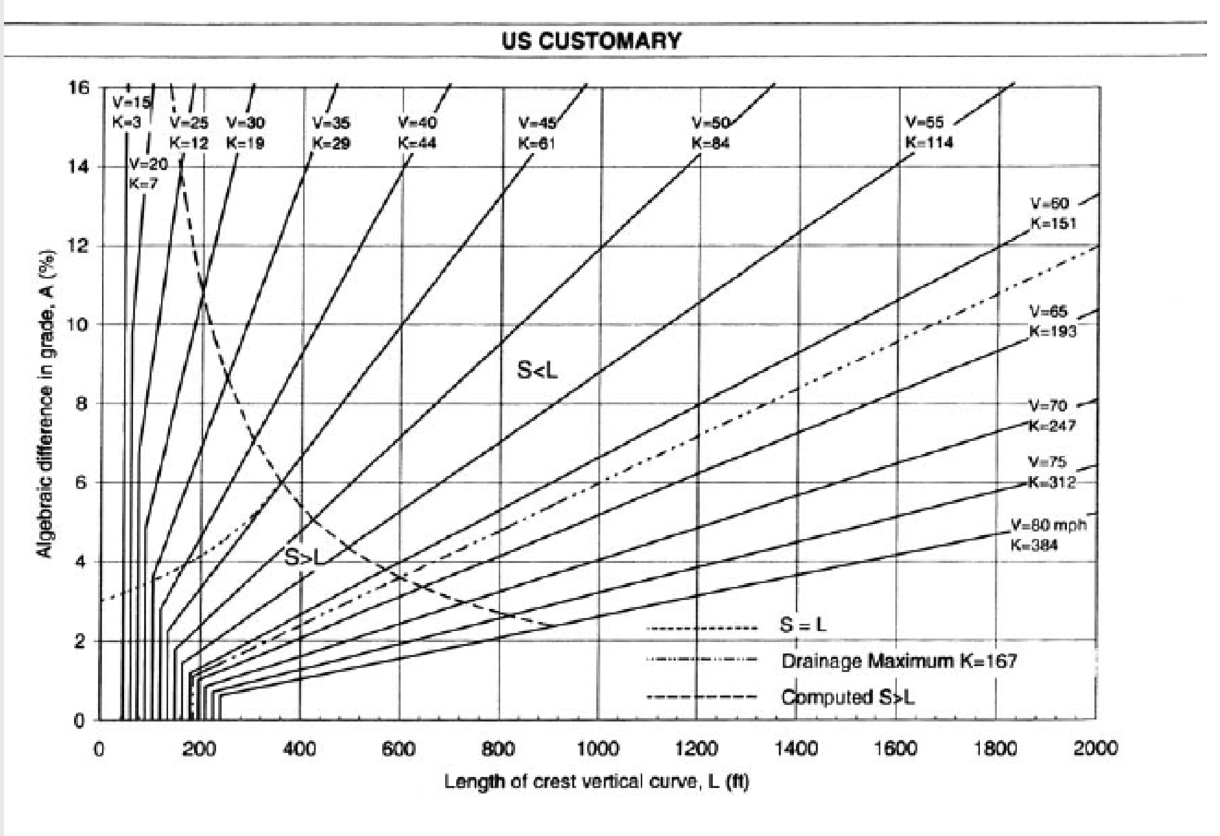
h_1=Height of eye above roadway surface (ft)

h_2=Height of object above roadway surface (ft)

Elements of Design: SSD & Vertical Alignment

EPG Category 230.2: Vertical Alignment

Calculating length of vertical curves based on stopping sight distance using graphs.



Elements of Design: SSD & Vertical Alignment

EPG Category 230.2: Vertical Alignment

Calculating length of vertical curves based on stopping sight distance using tables.

Metric				US Customary			
Design speed (km/h)	Stopping sight distance (m)	Rate of vertical curvature, K[a]		Design speed (mph)	Stopping sight distance (ft)	Rate of vertical curvature, K[a]	
		Calculated	Design			Calculated	Design
20	20	0.6	1	15	80	3.0	3
30	35	1.9	2	20	115	6.1	7
40	50	3.8	4	25	155	11.1	12
50	65	6.4	7	30	200	18.5	19
60	85	11.0	11	35	250	29.0	29
70	105	16.8	17	40	305	43.1	44
80	130	25.7	26	45	360	60.1	61
90	160	38.9	39	50	425	83.7	84
100	185	52.0	52	55	495	113.5	114
110	220	73.6	74	60	570	150.6	151
120	250	95.0	95	65	645	192.8	193
130	285	123.4	124	70	730	246.9	247
				75	820	311.6	312
				80	910	383.7	384

[a] Rate of vertical curvature, K, is the length of curve per percent algebraic difference in intersecting grades (A). K = L/A

Elements of Design: SSD & Vertical Alignment

EPG Category 230.2: Vertical Alignment

Vertical SSD and Length of Sag Vertical Curves

Length of sag curves are based on headlight sight distance with the following assumptions (AASHTO Green Book):

- Headlight height = 2 ft
- 1 degree upward divergence of light beam from the longitudinal axis of vehicle.

When taking crest vertical curve lengths into consideration, the equation to be used is:

L=KA Where, **L=Length of Vertical Curve (ft)**

A=Algebraic difference in grades, percent

K=Values listed in Green Book for sag curves

Elements of Design: SSD & Vertical Alignment

EPG Category 230.2: Vertical Alignment

Grades and Vertical Curves

Grades play a greater influence on trucks than passenger cars.

Studies show that trucks increase in speed by up to about 5% on down grades, and decrease in speed up to 7% on up grades.

In recreational routes where the low percentage of trucks does not warrant a climbing lane, designer should consider adding an additional lane.

AASHTO Recommendations on Control Grades for Design

Maximum grades of 5% are considered for 70 mph design speed

For 30 mph design speed, grades should be kept between 7-12% depending on terrain

Minimum grades of 0.5% is typically used.

Maximum grades can be determined based on AASHTO Green book tables.

Elements of Design: SSD & Vertical Alignment

EPG Category 230.2: Vertical Alignment

Minimum Design Criteria Guidelines

- ✓ Min. desirable rate of grade = 0.5%
- ✓ Min. ditch grade = 0.3% (0.3’ per every 100’)
- ✓ PGL on flood plains must keep shoulders at min. 1 ft above the design high water (DHW).
- ✓ Min. length of vertical curve = 300 ft when practical

AASHTO Green Book Guidelines for Selecting Max. Rate of Grade

Minor Roads		Major Roads	
Local Rural Roads	Chapter 5	Rural Arterials	Chapter 7
Local Urban Roads	Chapter 5	Urban Arterials	Chapter 7
Special Purpose Rd	Chapter 5	Rural Freeways	Chapter 8
Rural Collectors	Chapter 6	Urban Freeways	Chapter 8
Urban Collectors	Chapter 6		

Elements of Design: SSD & Vertical Alignment

EPG Category 230.2: Vertical Alignment

Intersections:

Side roads should connect at –1% rate of grade from shoulder of the through roadway, if practical.

Water should flow away from through roadway

Bridges:

Grades prior to and after bridge ends should maintain level for a distance of at least 50 ft.

Designer should avoid ending horizontal or vertical curves on bridges.

If bridge is on a curve, SE should be kept constant throughout the entire bridge.

All clearances under bridges must be met.

Elements of Design: Horizontal &Vertical Alignment

EPG Category 230: Alignments of the Roadway

Some recommendations for balancing horizontal and vertical alignment include:

- ✓ Tangent alignments or flat curves at the expense of long or steep grades and excessive curvature with flat grades are not a good design.
- ✓ Sharp horizontal curves should not be introduced at or near the top of a pronounced crest curve or at or near at the bottom of a sag curve.
- ✓ 2-lane roads need appropriate passing zones, so providing long tangent sections is recommendable.
- ✓ Both horizontal and vertical alignments should be as flat as possible at intersections to provide adequate sight distance.
- ✓ For divided highways, variation of median width and use of independent profiles and chains for the separate one-way roads are sometimes desirable.
- ✓ In residential areas, alignments should be designed to minimized nuisance to the neighborhood.
- ✓ Roadway aesthetics are important; design should combine the natural and manmade features of the land to provide a scenic view.
- ✓ Utilize design software 3D view capabilities of your horizontal and vertical alignment during the preliminary plan stage.

Elements of Design: Horizontal &Vertical Alignment

EPG Category 230: Alignments of the Roadway

Ramps:

Grade controls for ramps that intersect the crossroads are the same as for intersections.

For merging ramps, grades are established by projecting the through roadway profile grade to the ramp edge of pavement for the tangent section of the ramp.

For the curve on the ramp, the horizontal alignment and superelevation must be taking into account while projecting grades/elevations to the baseline of the ramp.

The picture in next slide graphically shows this procedure.

Elements of Design: Horizontal &Vertical Alignment

EPG Category 230: Alignments of the Roadway