The following equations are used to compute minimum length of vertical curve for both design option stated above:

When S is less than L

$$L_{min} = \frac{AS^2}{200\left(\sqrt{h1}+\sqrt{h2}\right)^2} \quad \text{...47}$$

When S is greater than L

$$L_{min} = 2S - \frac{200\left(\sqrt{h1}+\sqrt{h2}\right)^2}{A} \quad \text{...48}$$

Where:

L is length of vertical curve, *m*

A is algebraic difference in grades, *%*

S is sight distance, *m*

h1 is height of eye above roadway surface, *m*

h2 is height of object above roadway surface, *m*

Based on AASHTO's G.D policy, the values of h1 and h2 are 1.08 and 0.6 m, respectively. So by applying these values in equations above results, we get:

When S is less than L

$$L_{min} = \frac{AS^2}{658} \quad \text{...49}$$

When S is greater than L

$$L_{min} = 2S - \frac{658}{A} \quad \text{..50}$$

Design controls: stopping sight distance

Equation 49 (for S is less than L) can be rewritten as follows;

L= K. A ……………………………………………………………………….51

Where;

$K = S^2 / 658$ ……………………………………………………………………….52

And, K value represent the length of curve for each 1 degree change in the grade.

It should be noted in practice that when S > L, the calculated minimum length will be small and impractical for design consideration. Consequently, the designer should adopt minimum of crest vertical curve of L=0.6V (where L and V represent length of curve and design speed in Km/h, respectively) or use the first equation 49 to compute the design minimum length of curve. Figure 1.37 and Table 1.10 illustrate design controls for crest vertical curves based on stopping sight distance.

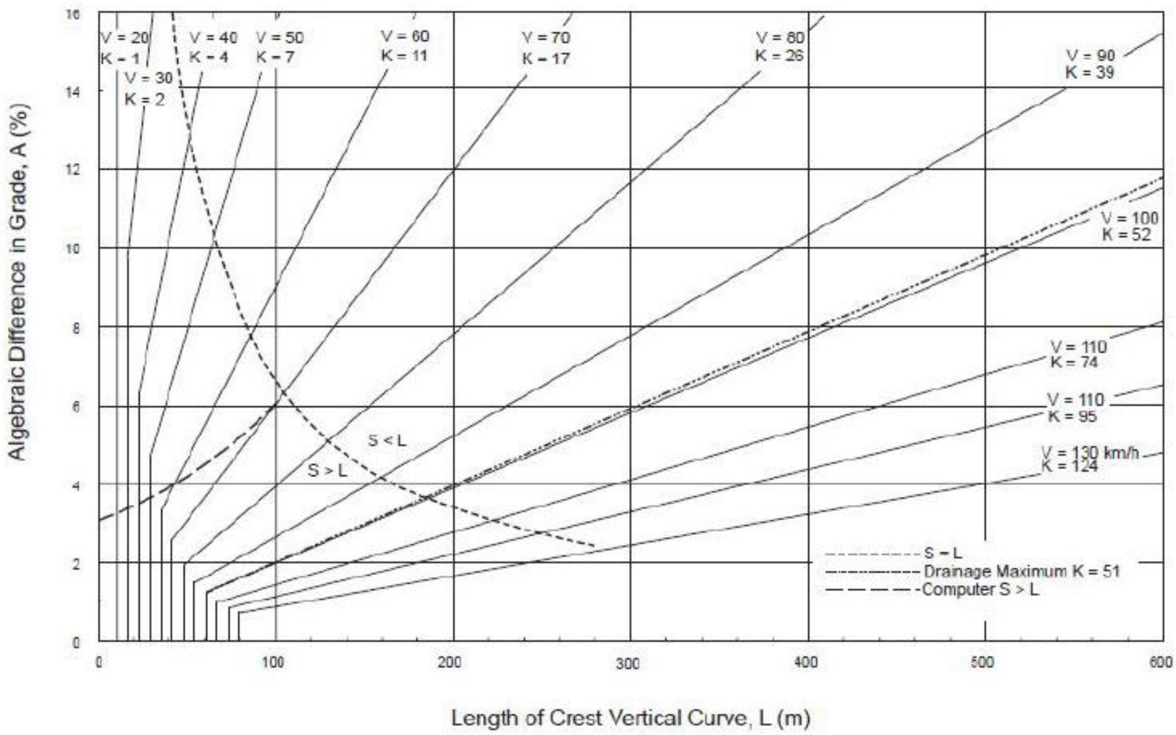

Figure 1.37: Design controls for crest curve

Table 1.10: Design controls for crest vertical curves based on stopping sight distance.

Metric				U.S. 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

Design controls: passing sight distance

Based on AASHTO's G.D policy, both values of h1 and h2 (in case of passing sight distance application as shown in Figure 1.38) should be adopted as 1.08. By applying these values in equations 47 and 48, we get:

When S is less than L

$$L_{min} = \frac{AS^2}{864} \qquad \text{.......53}$$

When S is greater than L

$$L_{min} = 2S - \frac{864}{A} \qquad \text{.......54}$$

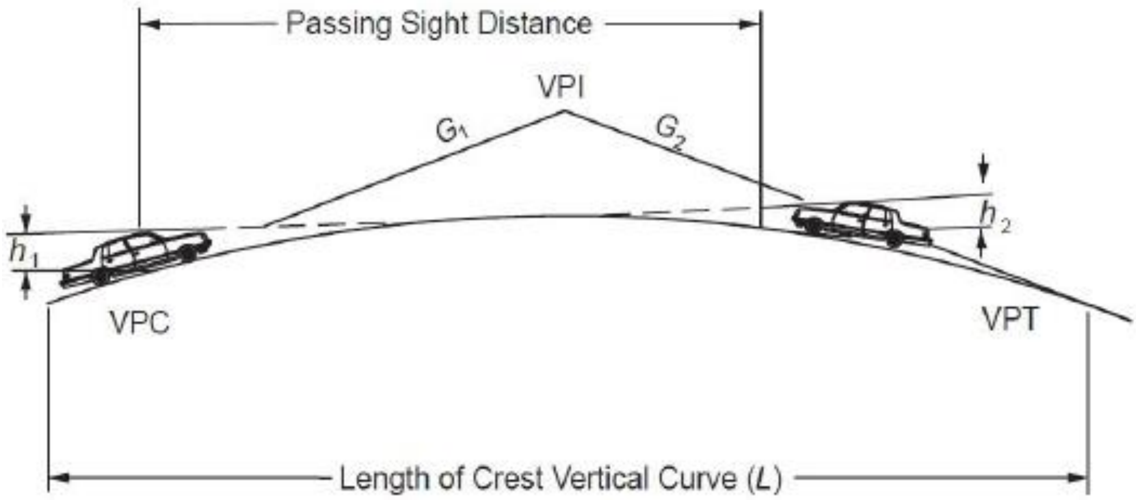

Figure 1.38: Passing sight distance on crest vertical

Table 1.11: Design controls for crest vertical curves based on passing sight distance

Metric			U.S. Customary		
Design Speed (km/h)	Passing Sight Distance (m)	Rate of Vertical Curvature, K^a Design	Design Speed (mph)	Passing Sight Distance (ft)	Rate of Vertical Curvature, K^a Design
30	120	17	20	400	57
40	140	23	25	450	72
50	160	30	30	500	89
60	180	38	35	550	108
70	210	51	40	600	129
80	245	69	45	700	175
90	280	91	50	800	229
100	320	119	55	900	289
110	355	146	60	1000	357
120	395	181	65	1100	432
130	440	224	70	1200	514
			75	1300	604
			80	1400	700

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

1.6.5.7.2 Sag vertical Curves

Having mentioned that the minimum length of sag vertical curve is governed by four criteria, which include:

1. Sight distance requirements.
2. Comfort requirements.
3. Appearance requirements.
4. Drainage requirements

Sag curve minimum length based on sight distance requirements

Sight distance in this type of highways depends on the lighted part of the roadway ahead for the driver as shown in Figures 1.39. This is called as headlight sight distance as previously defined. On day time or on well-lit roadway at night, there is no problem with sight distance on this type of curves. Headlight sight distance is therefore mainly used by most highway department to estimate the length of the sag curve.

Figure 1.39: Sag vertical curve at day and night time

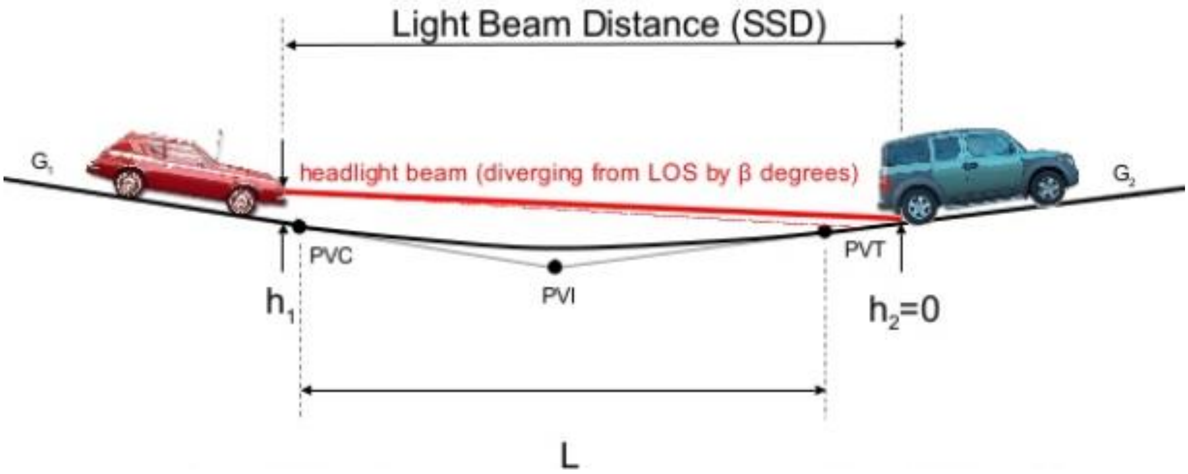

Figure 1.40: headlight (stopping) sight distance on crest vertical

According to sight distance requirement

When S is less than L

$$L_{min} = \frac{AS^2}{200(h+\tan\beta)} \quad \ldots\ldots 55$$

When S is greater than L

$$L_{min} = 2S - \frac{200(h+\tan\beta)}{A} \quad \ldots\ldots 56$$

Based on AASHTO's G.D policy, values of h and β are 0.6m and 1° respectively. And by applying these values, we get

When S is less than L

$$L_{min} = \frac{AS^2}{120+3.5\,S} \quad \ldots\ldots 57$$

When S is greater than L

$$L_{min} = 2S - \frac{120+3.5\,S}{A} \quad \ldots\ldots 58$$

Table 1.13 presents design controls for sag vertical curves based on stopping sight distance.

Sag curve minimum length based on driver comfort

Unlike on crest vertical curves, vehicle on sag curve is under a combination of gravitational and centrifugal forces. This combination may apply discomfort to the driver on this type of curves. To satisfy this criterion, the minimum length of curve should be estimated from the following formula.

$$L = \frac{AV^2}{395} \quad \text{.....59}$$

Sag curve minimum length based on general appearance

Vertical curves are normally provided at all change in grade. However, for the slight change in grade (small A values), high K values are frequently provided to make sure that an appropriate appearance exist. Table 1.12 illustrates the maximum change in gradient that do not require a vertical curves and also the minimum length of curves for satisfactory appearance.

Table 1.12: Appearance requirement requirements

Design speed (km/h)	*Maximum gradient change without vertical curve (%)*	*Minimum length of vertical curve for satisfactory appearance (m)*
40	1.0	30
60	0.8	50
80	0.6	80
100	0.4	100
120	0.2	150

Sag curve minimum length based on drainage requirements

This criterion has to be considered in the case of curbed roads. In this scenario, the requirement is normally focuses on the maximum length whereas minimum lengths for other criteria are required. To satisfy this criterion, the maximum length should ensure that there is a minimum grade of 0.35 at the lowest 15 m of the curve. The maximum length to meet this requirement is normally equal the minimum length for other criterion for speed over 60 km/h.

Q1*: An equal-tangent vertical curve is to be constructed between grades of -2% (initial) and +1.0% (final). The PVI is at station 3 +352.8 and at elevation 128.016m. Due to a street crossing the roadway, the elevation of the roadway at station 3+ 413.76 must be at 129.388m. Design the curve*

Q2*: A vertical curve crosses a 1.219m diameter pipe at right angles. The pipe is located at station 3+ 378.708 and its centreline is at elevation 332.72m. The PVI of the vertical curve is at station 3+352.8 and elevation 334.792m. The vertical curve is equal tangent 182.88m long, and connects an initial grade of +1.2% and a final grade of -1.08%. Using offsets, determine the depth, below the surface of the curve, of the top of the pipe and determine the station of the highest point on the curve.*

Q3: *A highway is being designed to AASHTO guidelines with 110 Km/h design speed, and at one section, an equal-tangent vertical curve must be designed to connect grades of +1.0% and -2.0%. Determine the minimum length of curve necessary to meet SSD requirements.*

Q4*: A sag vertical curve joins a -3% grade and a +3% grade. If the PVI of the grades is at station 132+74.04 and has an elevation of 71.63m, determine station and elevation of the BVC and EVC for a design speed of 110Km/h. Also, compute the elevation on the curve at 20m intervals. (Hint: K value for design speed of 110Km/h is 55.*

Q5: *A crest vertical curve is to be designed to join a +3% grade with a -2% grade at a section of a two-lane highway. Determine the minimum length of the curve if the design speed of the highway is 100 Km/h, and a perception-reaction time of 2.5 sec. The deceleration rate for braking (a) is 3.5 m/sec^2.*

Q6*: An existing vertical curve on a highway joins a +4.4% grade with a -4.4% grade. If the length of the curve is 83.82m, what is the maximum safe speed on this curve? What speed should be posted if 5 mph increments are used? Assume a is 3.5 m/sec^2, perception-reaction time is 2.5 sec, and that Sight distance is less than length of vertical curve, L.*

Q7*: A sag vertical curve is to be designed to join a -5% grade to a +2% grade. If the design speed is 65 Km/h, determine the minimum length of the curve that will satisfy all criteria. Assume a is 3.5 m /sec^2 and perception-reaction time is 2.5 sec*