Estimation of Suitable Grade Value for Stopping Sight Distance Computation on Vertical Curves

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Abstract

The purpose of highway geometric design is to provide safe and economical highways. One of the utmost important geometric design element for safely travel that should be satisfied is visibility on designed road. This can achieved by providing adequate sight distance in both horizontal and vertical alignments. Minimum sight distance that should be provided at all points along highway is stopping sight distance SSD. In the design of vertical curves AASHTO's Geometric design Policy uses the sight distance requirement as a major criterion in curve length determination. Moreover, sight distance has great effect on highway constructional cost because more required sight distance means more vertical curve length, which in turn means more earthwork materials. Consequently, safety and economics can be considered as a major criterion in design of highways. The AASHTO's model involved design speed, perception-reaction time, and frication factor as a parameters used for SSD computations on level sections. On inclined surfaces, an additional parameter denoted by (G), which reflect grade of sloped surface on SSD. In the present paper a new approximate methodology and Equations are formulated though which a suitable design grade value can be estimated on vertical curves where the grade not constant then utilizing this value to compute SSD on these curves and hence compute vertical curve length corrected for grade effect. Generalization of present methodology is carried out by derivation a general mathematical solution. From these derivations it has been found that the suitable grade value for Type I and Type III (initial and final grade are descending and ascending) is half of the largest grade among G1 and G2. While the design grade value is the average value of G1 and G2 for Type II and Type IV (both grade are descending or ascending). Comparison with other grade estimation on vertical curves suggestions showed that the present methodology produces more reasonable and economical value because the obtained length is no longer to be uneconomical as compared with other suggestions. At the same time it provides a safe value used in all design cases those reflects the actual case as compared with other suggestions those ignored or reduced the effect of grade.

Introduction:

Safety and economics are the main objectives those must be verified in geometric design of highways. Visibility on designed road can be considered one of the most important geometric design requirements for safety of travel that should be satisfied. Therefore its necessary that the sight distance of adequate length must be provided to permit drivers enough time and distance to control their vehicle so that there are no unwarranted accidents (1).Actually, sight distance is a basic element of geometric design and has direct bearing on the quality and cost of highway (2). Minimum sight distance that must be provided at all points along the highway is called stopping sight distance (3). SSD can be restricted by horizontal and vertical alignment. Accordingly, both alignments should be designed to provide at least Stopping Sight Distance.

The basic model to define the stopping sight distance was developed in 1940s (4). The main parameters used in this model are perception-reaction time, design speed, friction factor, and grade value for sloped sections. These above mentioned factors usually reflect the highway prevailing conditions such as highway functional class, highway pavement conditions, and driver behavior. Design speed is largely depends on highway functional, while perception reaction time is assigned as 2.5 sec. (AASHTO).friction factor (sometimes called longitudinal friction factor) is related to design speed . Finally, the value of grade represents the slope of inclined surface that the vehicle may run on it.

In the present paper, a simple approximate methodology is formulated through which a suitable design grade value for SSD computations can be estimated on vertical curves where the value of grade not constant. The proposed methodology allows the user to estimate grade value easily without complicated procedures. Derivations of Equations for grade estimation on vertical curve Types is also carried out. Finally a comparison with the suggested procedure is also presented.

Stopping Sight Distance Fundamentals:

Stopping sight distance as defined by AASHTO's Geometric design policy is the length of roadway that a driver must be able to see ahead. Also AASHTO (3) stated that the minimum sight distance at any point on the highway should be long enough to enable vehicle traveling at or near design speed to stop safely before sticking a stationary object in its path. Sight line may be restricted by horizontal or vertical directions .consequently both horizontal and vertical alignments should be designed to provide at least SSD.

The AASHTO's SSD model consists of two distances. The first distance is the perception-reaction distance, i.e. the distance traveled during perception-reaction time. The other distance is the braking distance or in other words, distance traveled from the moment the brakes are applied to the moment the vehicle is stopped. The mathematical form is (3):

$$SSD = 0.278.V.t + \frac{V^2}{254.f} \quad ....(1)$$

where:

V= design speed (Kph)

t=perception-reaction time (sec.)

f= friction factor

Above equation was derived for level section. Stopping sight distance is increased on downgrade and decreased on upgrade. Therefore SSD is computed on inclined sections by the following model (3):

$$SSD = 0.278.V.t + \frac{V^2}{254(f \pm G)} \quad ....(2)$$

where:

G= Grade (%), + for upgrade, - for downgrade
V, t, f= as stated earlier.

The question that arises now which grade value should be used in computing SSD on vertical curves where the grade value is not constant. Mannering (5) stated that the assumption that G=0 in SSD computation on vertical curve is not strictly correct. He also reported that if the initial grade or final grade is used the designer in this case will be underestimating or overestimating the stopping sight distance.

Vertical Curve and Stopping Sight Distance:

Vertical curve provide a gradual change between two grades, so vehicle may run smoothly and efficiently. Vertical curve are classified as crest and sag vertical curves. The various shapes for Vertical curves as reported by AASHTO Geometric Design Policy are shown in Figure (1)

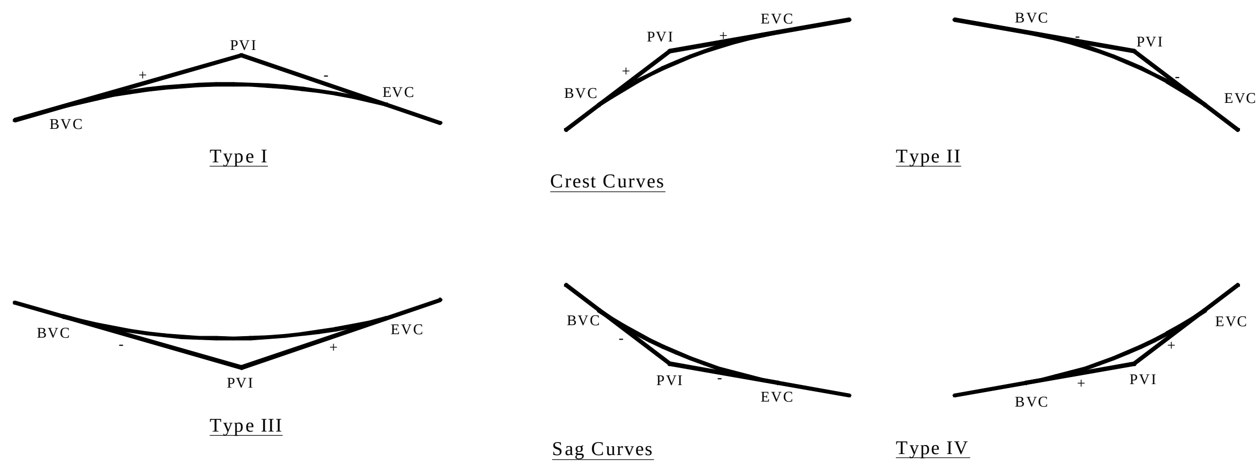

FIGURE (1): Various Types of vertical curves as defined by AASHTO's Geometric Design Policy 1994

In design of vertical curves, AASHTO (5) uses the sight distance requirements as a major criterion in length of curve computations. SSD is considered an important factor on highway construction cost because more required length of vertical curves, which in turn means more earthwork materials. It is usually to use stopping sight distance equal to sight distance in length of curve determination since it's impractical to design vertical curve to provide passing sight distance because of high cost where crest cuts are involved and difficulty of fitting the required long vertical curve to the terrain particularly for high speed roads (6). Length determination for vertical curves is found by the following subsections

Crest vertical curves

The minimum length of crest vertical curve to provide required sight distance is as follows (3, 6):

$$L_{\min.} = \frac{A.S^2}{200(\sqrt{h_1}+\sqrt{h_2})} \;.....S < L..........(3)$$

$$L_{\min.} = 2.S - \frac{200(\sqrt{h_1}+\sqrt{h_2})}{A} \;.....S > L..........(4)$$

where:
$L_{min.}$ = minimum length of vertical curve (m)
S= Sight distance (m)
$h_{1=}$ driver's eye height (m)
h_2=object's height (m)
A= change in grade (%)

AASHTO design guidelines use h1= 1.07m, and h2=0.15 m to provide sight distance equal to stopping sight distance. Applying these values to equation (3) and (4) results (3, 6):

$$L_{\min.} = \frac{A.SSD^2}{404} \;.....S < L.....(5)$$

$$L_{\min.} = 2.SSD - \frac{404}{A} \;.....S > L.....(6)$$

Sag vertical curves:

The suggested equations for length of sag vertical curves determination to provide sight distance as follows (3, 6):

$$L_{\min.} = \frac{A.S^2}{200(\sqrt{h}+S\tan b)} \;.....S < L.....(7)$$

$$L_{\min.} = 2.S - \frac{200(h+S\tan b)}{A} \;.....S > L.....(8)$$

where:
$L_{min.}$ = minimum length of sag vertical curve (m)
S= Sight distance (m)

$h_{1=}$ height of headlight beam above roadway (m)
b = Angle of headlight relative to horizontal plane (degree)
A= change in grade (%)

For SSD requirements, AASHTO (3) policy use value of h=0.6m and b as 1^o. Substituting above criterions to equation (7) and (8) yields (3, 6):

$$L_{\min.} = \frac{A.SSD^2}{120 + 3.5SSD} .....S < L.....(9)$$

$$L_{\min.} = 2.S - \frac{120 + 3.5SSD}{A} ....S > L.....(10)$$

Equation (5) and (9) can be simplified (for SSD > L) as Lmin. =K.A where K is the length of curve per percent of grade change. AASHTO Policy (1994) has developed a design controls for both crest and sag vertical curve to estimate K-value and then easily compute the minimum length of vertical curve by multiplying these values by A.

AASHTO's Geometric design policy (1994) when developed these controls has ignored the effect of grade (G=0) in stopping sight distance computations (5) which is not strictly correct.

Mannering and Kilareski (5) stated that some caution should be exercised in using controls for vertical curves because that G=0 (in SSD determination) is used. Several studies were conducted to investigate effect of grade on stopping sight distance computation on vertical curves. Garber and Hoel (7) proposed the use of conservative grade; the smallest experienced in the direction of travel. Following Garber and Hoel, Harwood et. al. (7) reported that on vertical curves, where the grade is not constant the value of stopping sight distance can be based on the average grade over the braking distance. Unfortunately, this suggestion has no satisfactory mathematical justification Thomas et. al. (7) stated that the procedure advocated by AASHTO for the computation of minimum required length of vertical curve fail to acknowledge the impact of grade on stopping sight distance. Accordingly, they proposed a new methodology and model for the computation of controls parameters of vertical curve consistent with the maximum braking on these curves. They showed that their methodology gave long vertical curve length as compared with AASHTO's 1994 model. Consequently they recommended calibrating this methodology (7)

Proposed Method:

The stopping sight distance as shown earlier was developed for straight level or inclined section. On vertical curves, there are variable grade values along vertical curves (second-order equation). Applying the highest grade value will results in long sight distance as compared with current practice, which in turn will give long vertical curve length i.e., overestimate value. On the other hand, using lowest grade value will yields shorter stopping sight distance value i.e., underestimate value. Proposed method in present paper try to approximate the curved section as a straight one with acceptable accuracy. Hence estimating suitable and safe value of grade for using in SSD computations on vertical curves.

The Proposed method suggests determination the length of vertical curve with (G=0) assumption in SSD-computations. After computing all curve properties (BVC and EVC stations and elevations and high/low point) the curve must be divided into two straight lines as shown in Figure (2). The first line is the line that joins BVC point with (high/low) point. While the other line should join the high/low point and EVC point. Estimating the slope of each line and taking the largest value as a design grade value in re-computing Stopping Sight Distance. Obviously, the above approximation is not completely true especially in low rate of curvature. Therefore the present method is a self-correction procedure that uses the obtained design grade value in re-computing the stopping sight distance and then new vertical curve length corrected for grade effect.

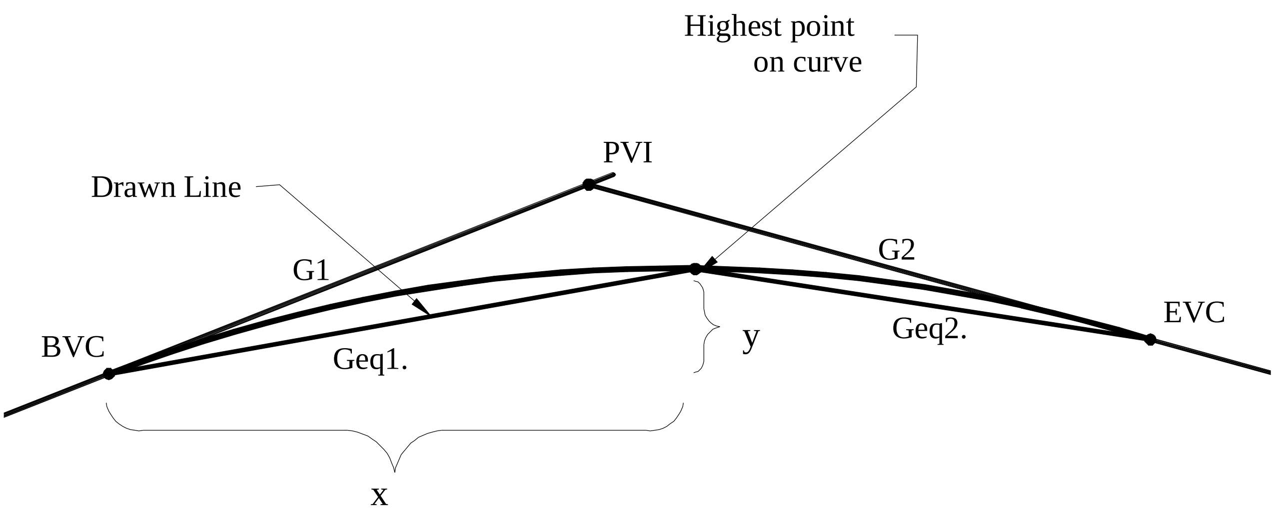

FIGURE (2): New Methodology Graphical Representation by Approximation Curved Section as Straight Section, Used for Type I and Type III

It suggested using above method for Type I and Type III of vertical curve. For Type II and Type IV vertical curve, the vertical curve should approximated to one straight section since high/low point is out-off curve i.e., no inflection point on curve , also the curve looks as one straight upgrade or downgrade section as shown in Figure (3). After determination vertical curve length on the basis of G=0 in SSD-computation as mentioned in case of Type I and Type III.

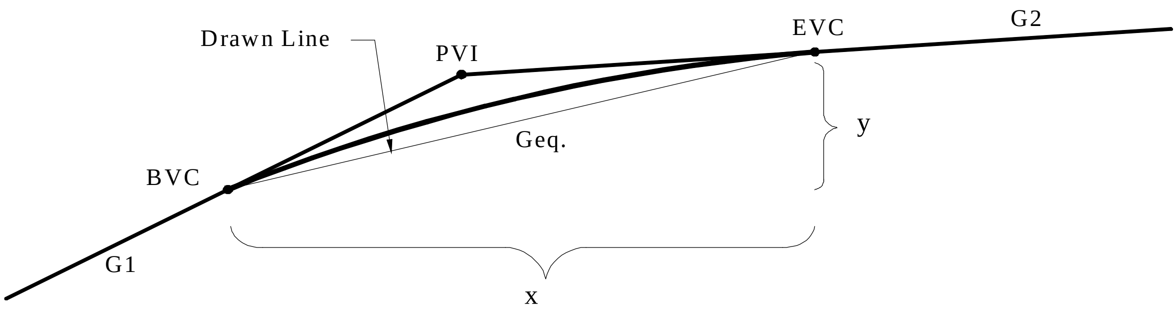

FIGURE (3): New Methodology Graphical representation by Approximation Curved Section as Straight Section, Used for Type II and Type IV

The straight line in this case should join the BVC point with EVC point. The above approximation is shown in Figure (3).

Previous methodology can be summarized as follows:

Type I and Type III vertical curves:

1. Compute the length of curve based on zero grade value in SSD-computation.
2. Compute the BVC,EVC and High/Low point stations and elevations
3. Draw a line joining BVC and High/Low point and another line join High/Low point with EVC point then compute the slope of each line and taking the largest one from them as a design grade value
4. Adopt the obtained grade as a design grade value for SSD computation
5. Compute vertical curve length corrected for grade effect based on computed SSD

Type II and Type IV vertical curves:

1. Compute the length of curve based on zero grade value in SSD-computation.
2. Compute the BVC,EVC and High/Low point stations and elevations
3. Draw a line joining BVC and EVC point compute the slope of the line as a design grade value
4. Adopt the obtained grade as a design grade value for SSD computation
5. Compute vertical curve length corrected for grade effect based on computed SSD

Derivations and Generalization of Proposed Method:

No doubt that the current procedure is a time consuming and exhaustive. Therefore an attempt to generalize the previous procedure will do in the following paragraphs. To achieve above goal the previous method will derived in terms of symbols and the finding a general solution or direct value for use based on previous methodology.

Type I and Type III Vertical Curves:

Referring to Figure (2):

$$Geq = \frac{y}{x} \ldots\ldots\ldots\ldots\ldots\ldots(11)$$

From properties of parabola:

$$y = \frac{G1}{100}.x + \frac{G2 - G1}{200.L}.x^2 \ldots\ldots\ldots\ldots\ldots(12)$$

Where:
Geq=Suitable grade value for use in SSD computation on vertical curve
y=Elevation difference between BVC and highest point on curve
x=Distance from BVC to highest point on curve
L=Length of Curve
G1=initial grade (%)
G2=Final grade (%)

But,

$$x = \frac{G1}{G1 - G2}.L \ldots\ldots\ldots\ldots\ldots(13)$$

Substituting equations (12) and (13) in Equation (11) results:

$$Geq = \frac{G1}{100} - \frac{G1 - G2}{200.L}.\frac{G1}{G1 - G2}.L \ldots\ldots\ldots\ldots\ldots(14)$$

Simplifying Equation (14) gives:

$$Geq = \frac{G1}{200} \ldots\ldots\ldots\ldots\ldots\ldots(15)$$

In the same manner, the grade value of other straight line is:

$$Geq = \frac{G2}{200} \ldots\ldots\ldots\ldots\ldots\ldots(15)$$

Type II and Type IV Vertical Curves:

Referring to Figure (3):

$$Geq = \frac{y}{x} \ldots\ldots\ldots\ldots\ldots\ldots(16)$$

i.e., $Geq = \frac{/ EVCelevation - BVCelevation /}{L} \ldots\ldots\ldots\ldots\ldots\ldots(16)$

where:
EVC elevation=End of Curve elevation
BVC elevation=Beginning of curve elevation

But,

$$EVCelevation = PVIelevation + \frac{G2}{100}.\frac{L}{2} \ldots\ldots\ldots\ldots\ldots\ldots(17)$$

and,

$$BVCelevation = PVIelevation - \frac{G1}{100}.\frac{L}{2}.......................(18)$$

Substituting Equation (17) and (18) in Equation (16) and simplifying yields:

$$Geq = \frac{G1+G2}{200}.......................(19)$$

From Equations (15) and (19) it can be said that for Type I and Type III ,the suitable grade value is equal to half of largest absolute value among G1 and G2 i.e., $Geq = \frac{/Gl\arg e/}{2}$. For Type II and Type IV vertical curves, the suitable grade value is equal to the average value of G1 and G2 values i.e., $Geq = \frac{/G1+G2/}{2}$. To take the worst case into consideration, the suitable grade value obtained above must be applied with negative sign into SSD-equation.

Comparison with Other Suggestion:

As stated earlier, several suggestions were developed to estimate the grade value on vertical curves. One of them is Garber and Hoel (1988) suggestion in which the authors propose using the most conservative grade; smallest value in the direction of travel. In fact, this proposal is most suitable when the difference between initial and final grades is small. When the difference is high, the estimated grade value doesn't represent the actual case that occur in the field

The second suggestion was proposed by Harwood which suggest the use average grade value. Actually, Harwood proposal is most suitable to use in all cases but some times gives overestimate value results. This situation occurs in Type I and Type III when initial grade value approaches final grade value.

AASHTO (1994) geometric design policy when developed vertical curves controls has ignored the effect of grade in stopping sight distance on vertical curves.

The proposed method in the present paper take into consideration the actual cases those occur in the field by Approximation the actual curve shape into straight sections. Proposed method uses two criterions, first one is economics by finding reasonable value with mathematical justification as minimum as possible. On the other hand, the second criterion represents the safety by providing grade value that will provide SSD actually experienced on vertical curve

Conclusions and Recommendations:

In the present paper, a simple new methodology and equation was developed to estimate the suitable grade value for SSD-computations on various types of vertical curves were the grade is variable value then utilizing this value in length of vertical curve determination. From derivation the general equations for suitable grade estimation, It has been found that the suitable grade value for Type I (initial grade are ascending and final grade descending) and Type III (initial grade are descending ascending and final grade ascending) is half largest absolute value from G1 and G2 values. On the other hand, average grade values in case of Type II and Type IV (Both grade are ascending or descending) should be used. It should be noticed that the above suitable grade value should be applied with negative sign to reflect the worst case in the direction of travel.

Comparison with other suggestion showed that the current method procedure a more reasonable and economical value becomes the longer curve produce more earthwork materials especially in mountainous terrain. On the other hand, it provides more safe design value as compared with other suggestions those ignored or reduced the effect of grade. Moreover, it can be used as general method as compared with other suggestion those used in special cases.

APPENDIX I: NOTATIONS

$L_{min.}$ = Minimum length of vertical curve (m)
A= Change in Grade (%)
G1= initial grade (%)
G2=final grade (%)
b = Angle of headlight relative to horizontal plane (degree)
G= Grade (%)
V= Design speed (Kph)
t=Perception-reaction time (sec.)
f= Friction factor
S= Sight distance (m)
SSD=Stopping sight distance (m)
h_1= Driver eye height (m)
h_2=Object height (m)
A= Change in grade (%)
BVC =Beginning of Vertical Curve point
EVC=End of Vertical Curve point
PVI=Point of Vertical Intersection

Geq= Suitable grade value for use in SSD computation on vertical curve

APPENDIX II: REFERANCES

1. Sharma, S. K.," Principles', Practice, and Design of Highway Engineering", S. Chand Company Ltd., New Delhi, 1985.
2. Pouls, A.,Borovsky, S., and Livneh, M., "Limited Sight Distance Effect on Speed ", Journal of Transportation Engineering, Vol.105, Sept.,1979.
3. American Association for State Highway and Transportation Officials (AASHTO),"A Policy on Geometric Design of Highways and Streets" , Washington DC,1994
4. Fambro, D. B., Fitzpatrick, K., and Koppa, R., “A New Stopping Sight Distance Model for Use in Highway Geometric Design", International Symposium on Highway Geometric Design Practices, Boston, USA, 1995.
5. Mannering, F. L., and Kilareski, W. P., "Principles of Highway Engineering and Traffic Analysis", Second Edition, John Wiley &Sons Inc.,1998
6. Farhan, Ahmed H., "Development of a Computer Program for Selecting Some Highway Geometric Design Elements", M.Sc. Thesis, University of Technology,Baghdad,2002
7. Thomas, N. E., Hafeez, and Evans B., "Revised Design Parameters for Vertical Curves", Journal of Transportation Engineering, Vol.124, No.1, July/August 1998.