Chapter III
Geometric design of Highways

Tewodros N.
www.tnigatu.wordpress.com
tedynihe@gmail.com

Lecture Overview

- Introduction
- Appropriate Geometric Standards
- Design Controls and Criteria
    - *Design Class*
    - Sight Distance
    - Design Vehicle
    - Traffic Volume and
    - Design Speed
- Geometric Design Elements
    - Horizontal Alignment
        - Straights (Tangents)
        - Circular Curves
        - Super elevation
        - Transition Curves
        - Widening of Curves
    - *Vertical Alignment*
        - *Vertical Curves*
        - *Length Of Vertical Curves*
        - *Sight Distances At Underpass Structures:*
        - *Grades and Grade Control*
    - Cross-Section

Vertical Alignment

- Consists of straight sections of the highway known as grades, or tangents, connected by vertical curves.
- The design involves the selection of suitable GRADES for the tangent sections and the design of the VERTICAL CURVES.
- The topography of the area through which the road traverses has a significant impact on the design of the vertical alignment.

GRADES

- Effect of grade is more pronounced on Heavy Vehicles than on Passenger Cars
- Maximum Grade on a highway should be carefully selected based on the design speed and design vehicle
- Grades of 4 to 5 % ⇒ little or no effect on passenger cars, except for those with high weight/horsepower ratios,
- Grade > 5% ⇒speed of passenger cars decrease on upgrades and increase on downgrades.
- Truck speeds may increase up to 5 percent on downgrades and decrease by 7 percent on upgrades

Maximum Grade

Design Speed	Maximum Grade
110 kph	5%
50 kph	7-12%
60 to 100 kph	Intermediate
Very Important highways	7-8%
Short grades less than 150m & one-way downgrades	1% steeper
Low volume highways	2% steeper

Maximum Gradients (ERA Manual)

Topography	Maximum Gradient (%), for Design Standard									
	DS1 to DS3		DS4 & DS5		DS6 to DS8		DS9		DS10	
	D	A	D	A	D	A	D	A	D	A
Flat	3	5	4	6	6	8	6	8	6	8
Rolling	4	6	5	7	7	9	7	9	7	9
Mountainous	6	8	7	9	10	12	13	15	14	16
Escarpment	6	8	7	9	10	12	13	15	14	16
Urban	6	8	7	9	7	9	7	9	7	9

Note: First value shown is desirable value (D), second is absolute value (A).

Minimum Grade

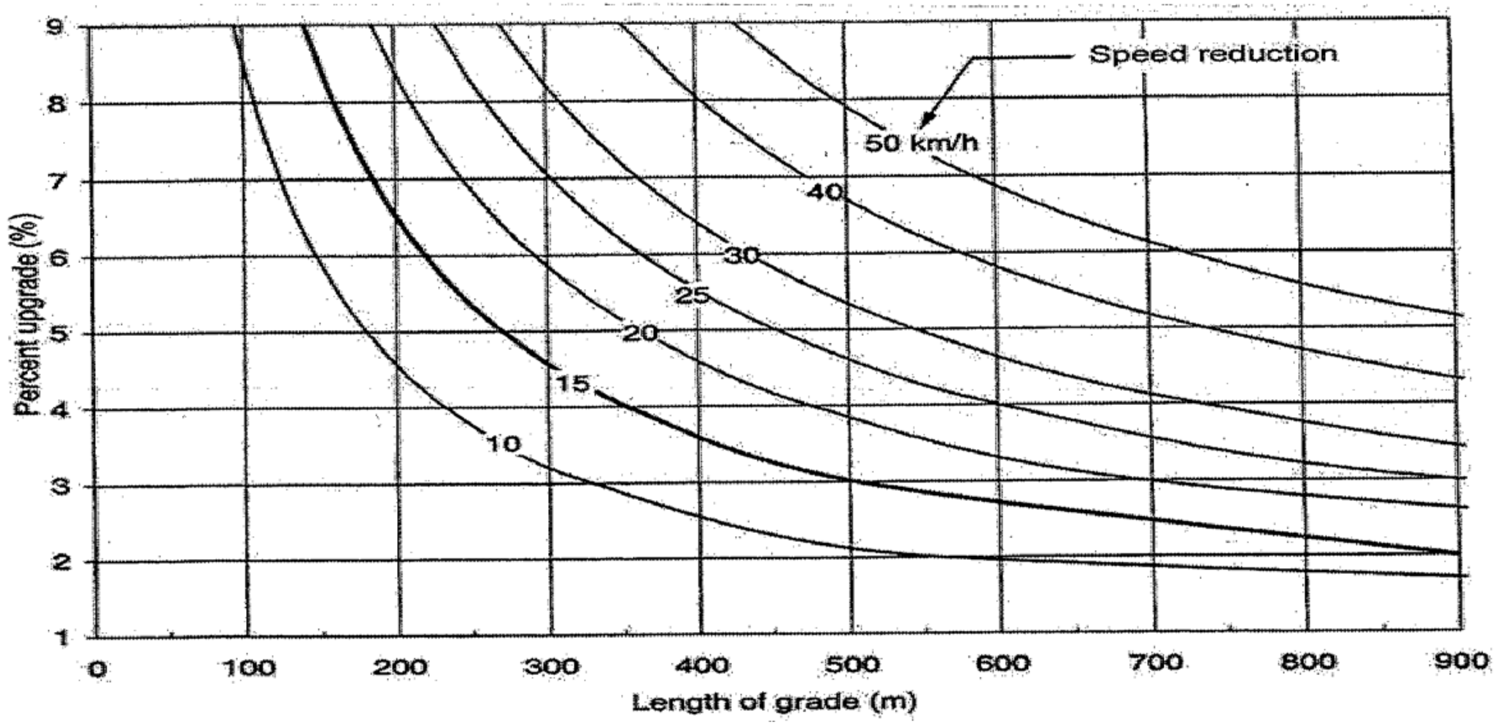
- Depend on the drainage conditions of the highway
- Zero-percent grades may be used on uncurbed pavements with adequate cross slopes to laterally drain the surface water
- For curbed pavements, however, a longitudinal grade should be provided to facilitate the longitudinal flow of the surface water
- A minimum grade of 0.5% is usually used; it may reduced to 0.3% on high-type pavement constructed on suitably crowned, firm ground.

Critical Length of Grade

- Indicates the *maximum length* of a designated upgrade on which a loaded truck can operate without an unreasonable reduction in speed
- For a given grade, lengths less than critical result in acceptable operation in the desired range of speeds.
- To maintain LOS on grades longer than critical
  - change in location to reduce grades.
  - addition of extra lanes (*climbing or crawler lanes*): data for critical lengths of grade are used with other pertinent considerations (such as traffic volume in relation to capacity, % heavies) to determine where added lanes are warranted.

Critical Length of Grade

- A common basis for determining critical length of grade is based on a ***reduction in speed of trucks*** below the ***average running speed of traffic***.



Critical lengths of grade for design, assumed typical heavy truck of 120kg/kw, entering speed=110km/h

Climbing Lane

- Additional lane for the upgrade direction of a two-lane highway where the grade, traffic volume, and heavy vehicle volume combine to degrade traffic operations from those on approach to the grade.
- The following three criteria, reflecting economic considerations, should be satisfied to justify a climbing lane:
  1. Upgrade traffic flow rate in excess of 200 vehicles per hour
  2. Upgrade truck flow rate in excess of 20 vehicles per hour
  3. One of the following conditions exists:
     - A 15km/h or grater speed reduction is expected for a typical heavy truck
     - Level-of-service E or F exists on the grade
     - A reduction of two or more levels of service is experienced when moving from the approach segment to the grade.

In addition, safety considerations may justify the addition of a climbing lane regardless of grade or traffic volumes

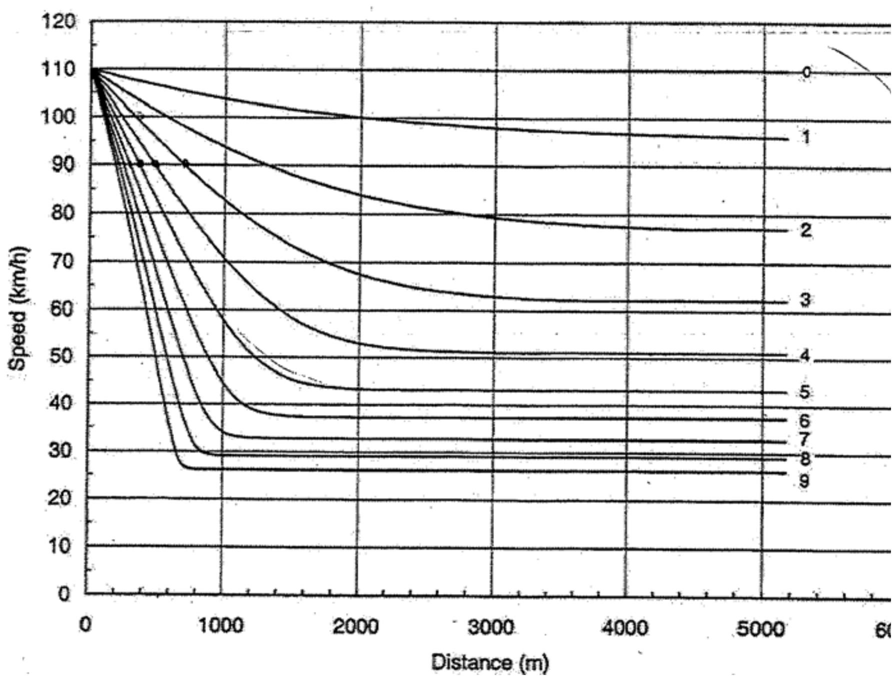
Climbing Lane

Design Class	Gradient (%)	Critical Length of Gradient above which a Climbing Lane is required (m)	Maximum Desirable Length of Gradient (m)
DS2 &3	4	300	900
DS2, 3 & 4	5	240	800
DS2, 3 & 4	6	200	700
DS2, 3 & 4	7	170	600
DS2, 3 & 4	8	150	500
DS2, 3 & 4	9	130	400
DS2, 3 & 4	10	Required	400
DS4	11	Required	400
DS4	12	Required	400

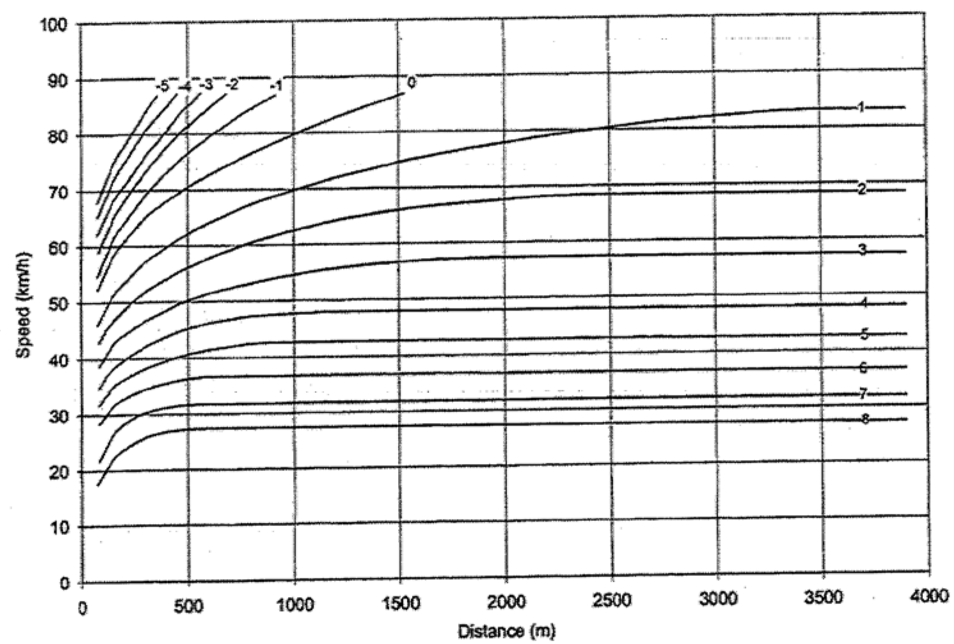
Climbing Lanes Length (ERA Manual)

Effect of Grade

- *Vehicle Operating Characteristics on Grades*: On upgrades, the maximum speed that can be maintained by a truck is dependent primarily on the length and steepness of the grade and the truck's weight/power ratio, which is the gross vehicle weight divided by the net engine power. Other factors that affect the average truck speed on a grade are the entering speed, the aerodynamic resistance, and skill of the driver.



Speed-Distance Curves for a Typical Heavy Truck of 120kg/kW for deceleration on Upgrades



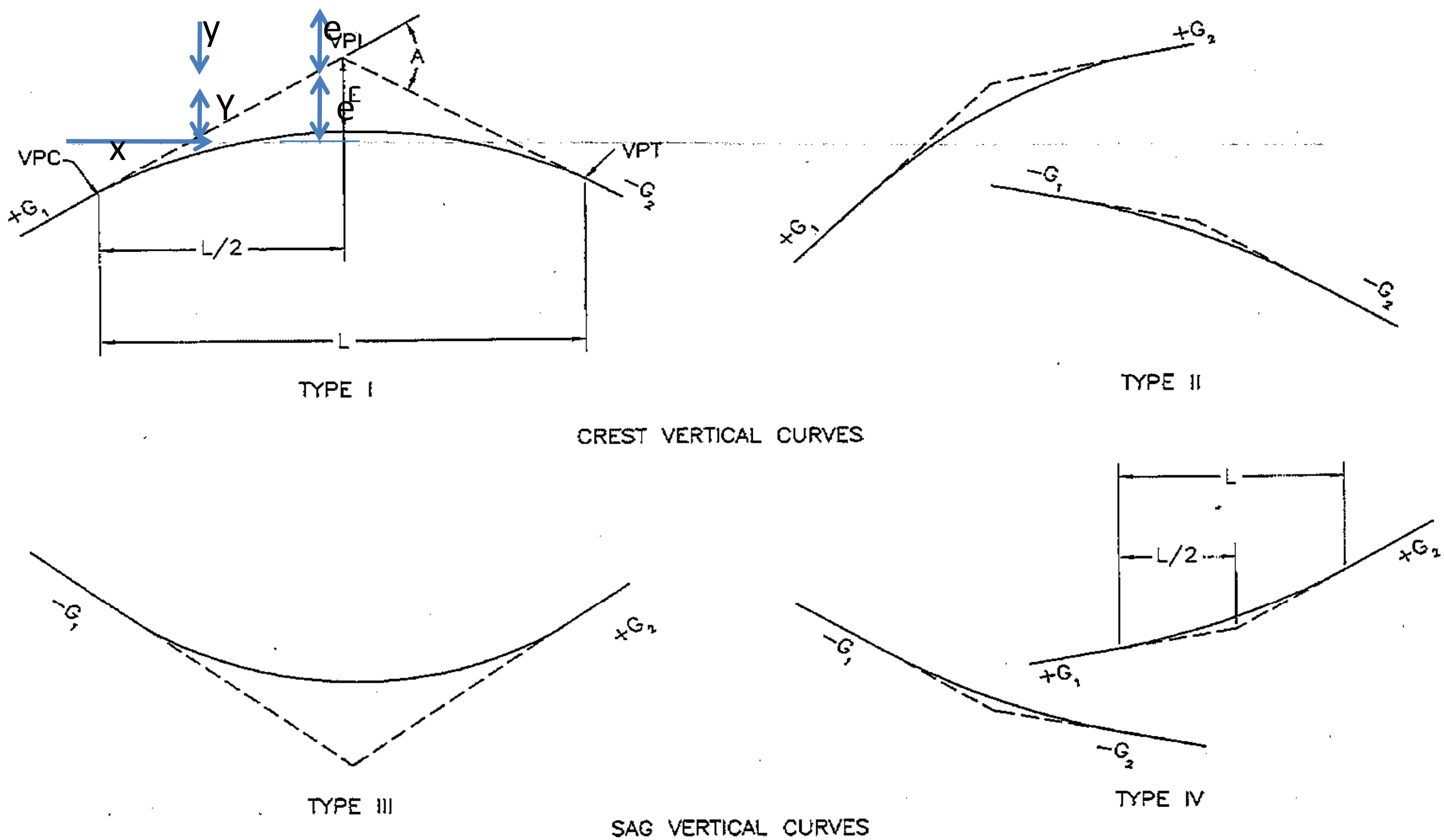
Speed-Distance Curves for Acceleration of a Typical Heavy Truck of 120kg/kW on Upgrades and Downgrades

Vertical Curves

- Are parabolic curves used to provide a gradual change from one tangent grade to another so that vehicles may run smoothly as they traverse the highway.
- Are of two types
  - Sag Vertical Curves
  - Crest Vertical Curves
- Design Criteria for vertical curves
  - Provision of minimum stopping sight distance
  - Adequate drainage
  - Comfortable in operation
  - Pleasant appearance

The first criterion is the only criterion associated with crest vertical curves, whereas all four criteria are associated with sag vertical curves.

Types of Vertical Curves



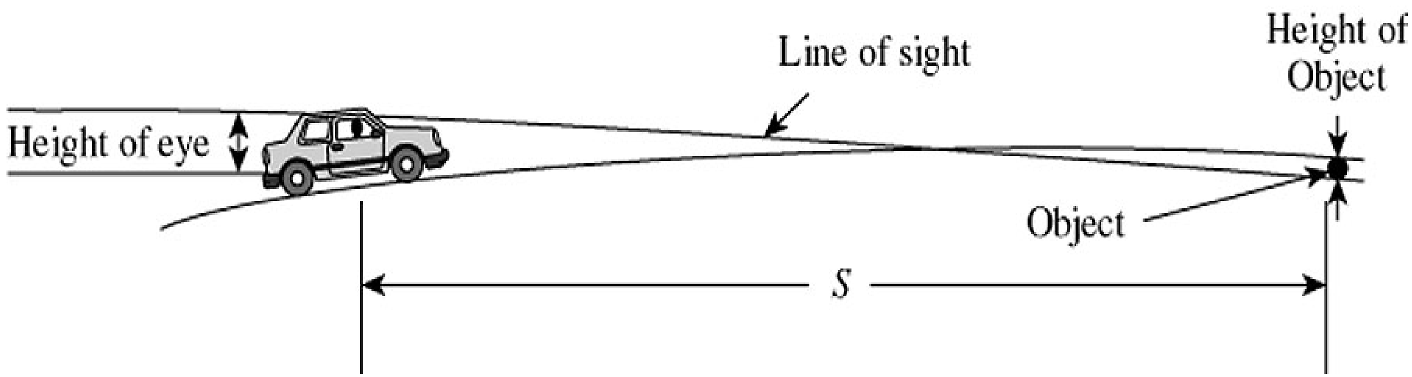
G_1 and G_2 = Tangent grades in percent
A = Algebraic difference in grade
L = Length of vertical curve

Crest Vertical Curves

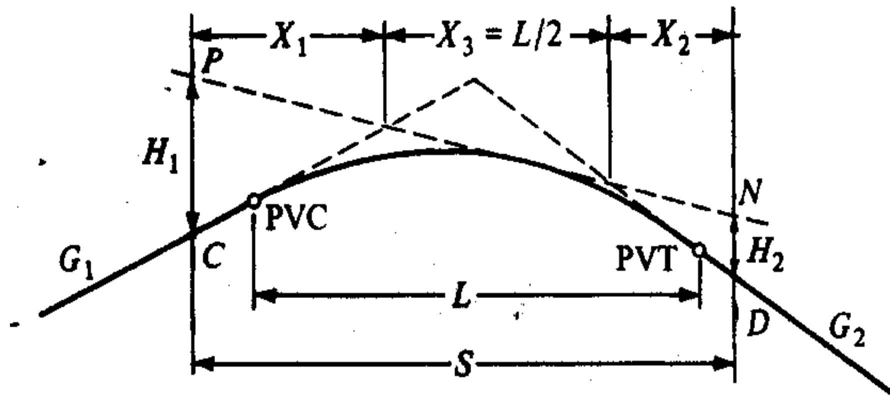
- Minimum length of the vertical curve (L) is determined by sight distance (SD) requirements
- That length is generally are satisfactory from the standpoint of safety, comfort, and appearance.
- Derivation is done for the two cases of:
  - SD > L
  - SD < L

Crest Vert. Curves

minimum length when S>L



Vehicle on the grade at C
H_1 height of the driver's eye at C
H_2 height of an object at D
PN is line of sight, and
S is the sight distance



Note that the line of sight is not necessarily horizontal, but in calculating the sight distance, the horizontal projection is considered

Crest Vert. Curves
Min. length – Derivation (S>L)

From the properties of the parabola,

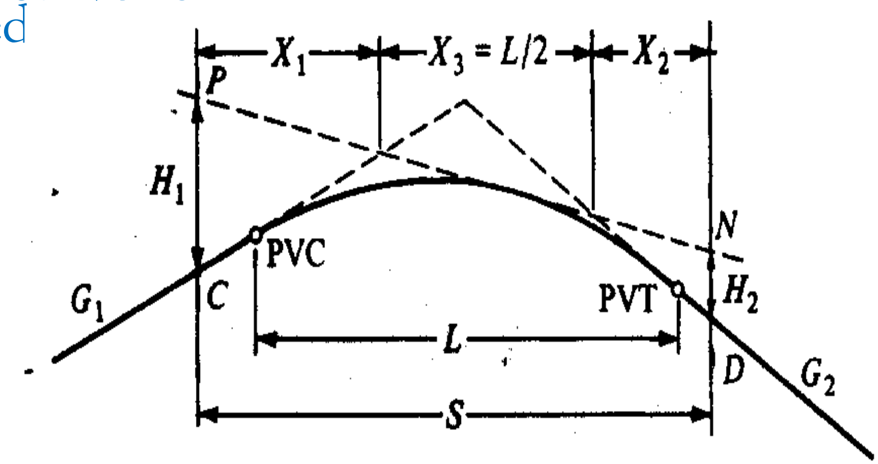
$X_3 = L/2$

The sight distance S is then given as

$S = X_1 + L/2 + X_2$

X_1 and X_2 can be found in terms of the grades G_1 and G_2 and their algebraic difference A. The minimum length of the vertical curve for the required sight distance is obtained

$$L = 2S - \frac{200\left(\sqrt{H_1} + \sqrt{H_2}\right)^2}{A}$$



where,

L = length of vertical curve, m

S = sight distance, m

A = algebraic difference in grades, %

H_1 = height of eye above roadway surfac

H_2 = height of object above roadway surface, m

Crest Vert. Curves
Min. length – Derivation (S>L)

- When the height of eye and the height of object are 1070 mm and 150 mm, respectively, as used for stopping sight distance, the length of the vertical curve is,

$$L = 2S - \frac{404}{A}$$

Crest Vert. Curves

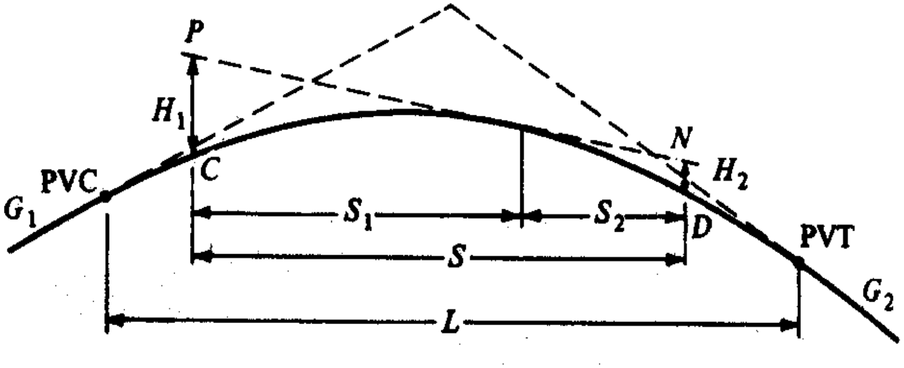
Min. length – Derivation (S<L)

Similarly:

$$L = \frac{AS^2}{200\left(\sqrt{H_1} + \sqrt{H_2}\right)^2}$$

Substituting 1070 mm for H1 and 150 mm for H2 gives

$$L = \frac{AS^2}{404}$$



Crest Vertical Curves

– **Design controls – stopping sight distance:** The minimum length of vertical curves for different values A to provide the minimum stopping sight distances for each design speed are shown in the next slide. The solid lines give minimum vertical curve length, on the basis of rounded values of K as determined from equation (i) and (j).

The short dashed curve at the lower left, crossing these lines, indicates where S = L. Note that to the right of the S = L line, the value of K, or length of vertical curve per percent change in A, is a simple and convenient expression of the design control.

$$L = KA \qquad \text{(L in m, A in percent)}$$

Crest Vertical Curves

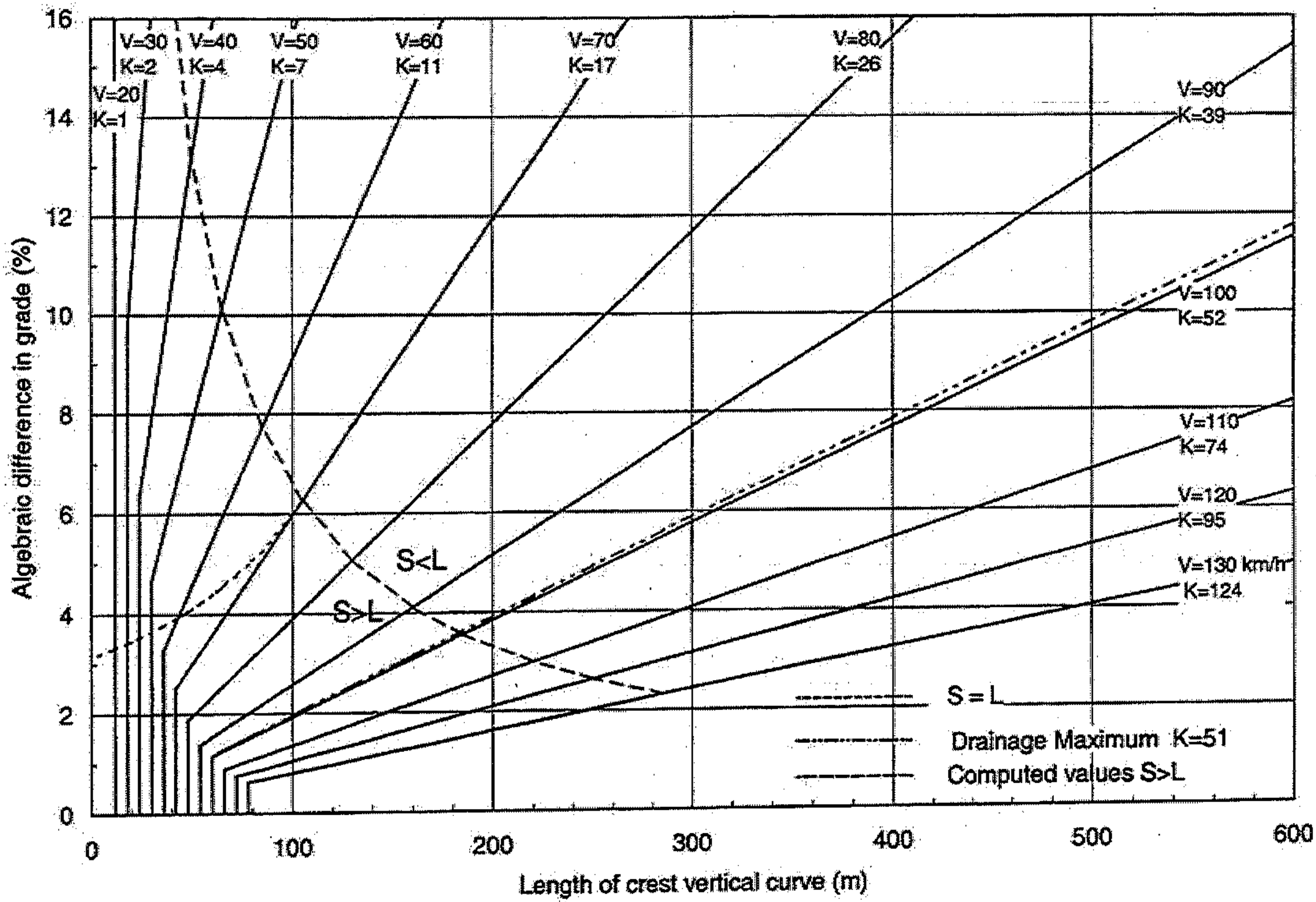


Fig.: Design Controls for Crest Vertical Curves – Open Road Conditions

Crest Vertical Curves

Metric			
Design speed (km/h)	Stopping sight distance (m)	Rate of vertical curvature, K^a	
		Calculated	Design
20	20	0.6	1
30	35	1.9	2
40	50	3.8	4
50	65	6.4	7
60	85	11.0	11
70	105	16.8	17
80	130	25.7	26
90	160	38.9	39
100	185	52.0	52
110	220	73.6	74
120	250	95.0	95
130	285	123.4	124

Table: Design Controls for Stopping Sight Distance and for Crest Vertical Curves

Design for Passing sight distance

Differ from those for stopping sight distance because of the different height criterion (i.e. 1300 mm height of object) results in the following specific formulas with the same terms as above:

When S > L,

$$L = 2S - \frac{946}{A}$$

When S < L,

$$L = \frac{AS^2}{946}$$

Design for Passing sight distance

Metric		
Design speed (km/h)	Passing sight distance (m)	Rate of vertical curvature, K^* design
30	200	46
40	270	84
50	345	138
60	410	195
70	485	272
80	540	338
90	615	438
100	670	520
110	730	617
120	775	695
130	815	769

Table: Design Controls for Crest Vertical Curves Based on Passing Sight Distance

Sag Vertical Curves

Design Criteria:

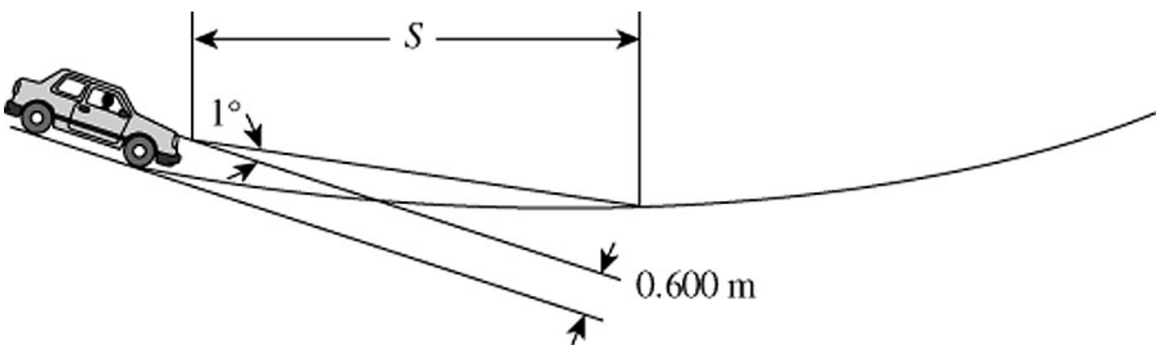
1. Headlight sight distance
2. Rider Comfort
3. Drainage Control
4. Aesthetics (rule of thumb)

Headlight Sight Distance, S

Height of the headlight =600mm

Upward divergence of the light beam = 1^{o}

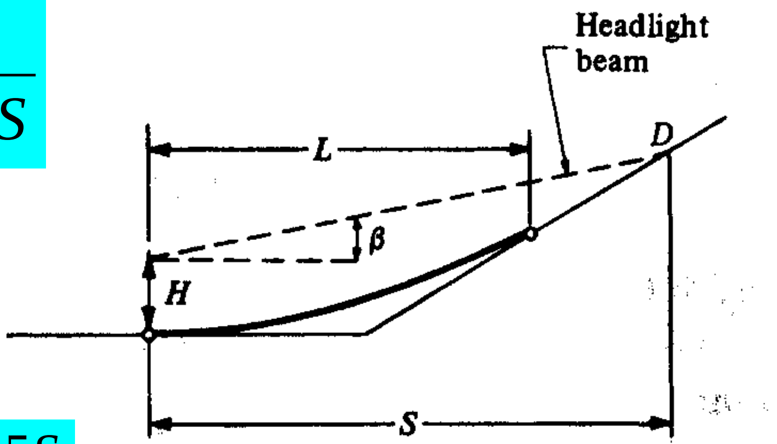
(The upward spread of the light beam provides some additional visible length, but that is generally ignored.)



Length of curve with adequate SD

When S<L:

$$L = \frac{AS^2}{200(0.6 + S\tan\beta)} = \frac{AS^2}{120 + 3.5S}$$



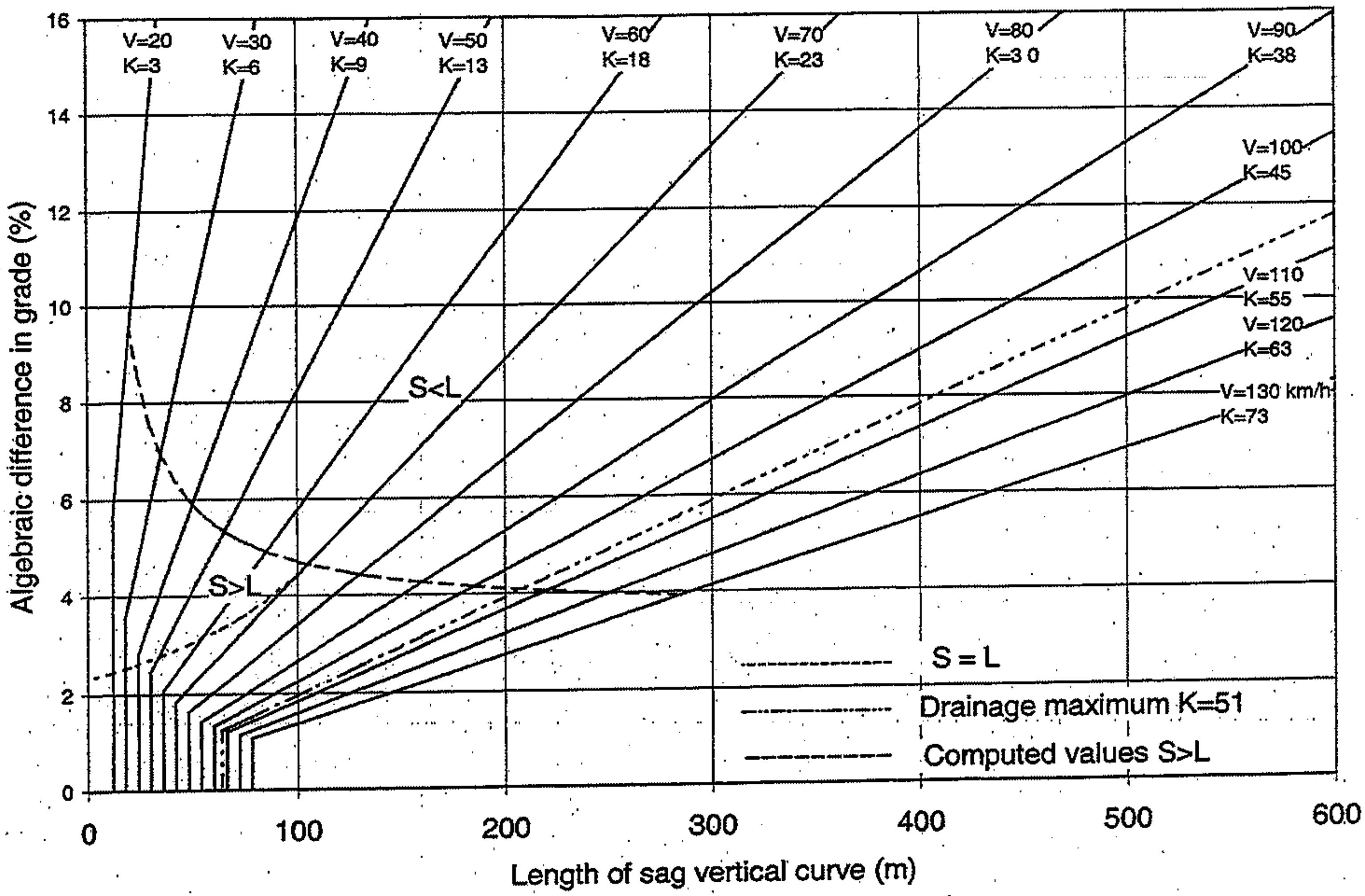
When S>L:

$$L = 2S - \frac{200(0.6 + S\tan\beta)}{A} = 2S - \frac{120 + 3.5S}{A}$$

L=length of curve (m), A=algebraic difference in grade (%), and S=headlight distance (m)

Length of curve with adequate SD

- For overall safety on highways, a sag vertical curve should be long enough that the light beam distance is nearly the same as the stopping distance.



Design Controls for Sag Vertical Curves – Open Road Conditions

Length of Curve for comfort

- Considers that both the gravitational and centrifugal forces act in combination, resulting in a greater effect than on a crest vertical curve
- Comfort is affected by:
  - weight carried, body suspension of the vehicle, and tire flexibility
  - Measuring Comfort = Difficult!
  - Indicator = radial acceleration is not greater than 0.3 m/s3
- The general expression for such a criterion is:

  V is the design speed, km/h.

$$L = \frac{AV^2}{395}$$

- Usually this length is about 50 percent of that required to satisfy the headlight sight distance at various design speeds (for normal conditions).

Min. Length for Aesthetics

- Rule of thumb

$$L_{\min} = 30A$$

- Longer curves are necessary for high type of highways to improve appearance.

Max. Length of Curve for drainage

Here the drainage criteria sets a limit on the MAXIMUM length of curve!

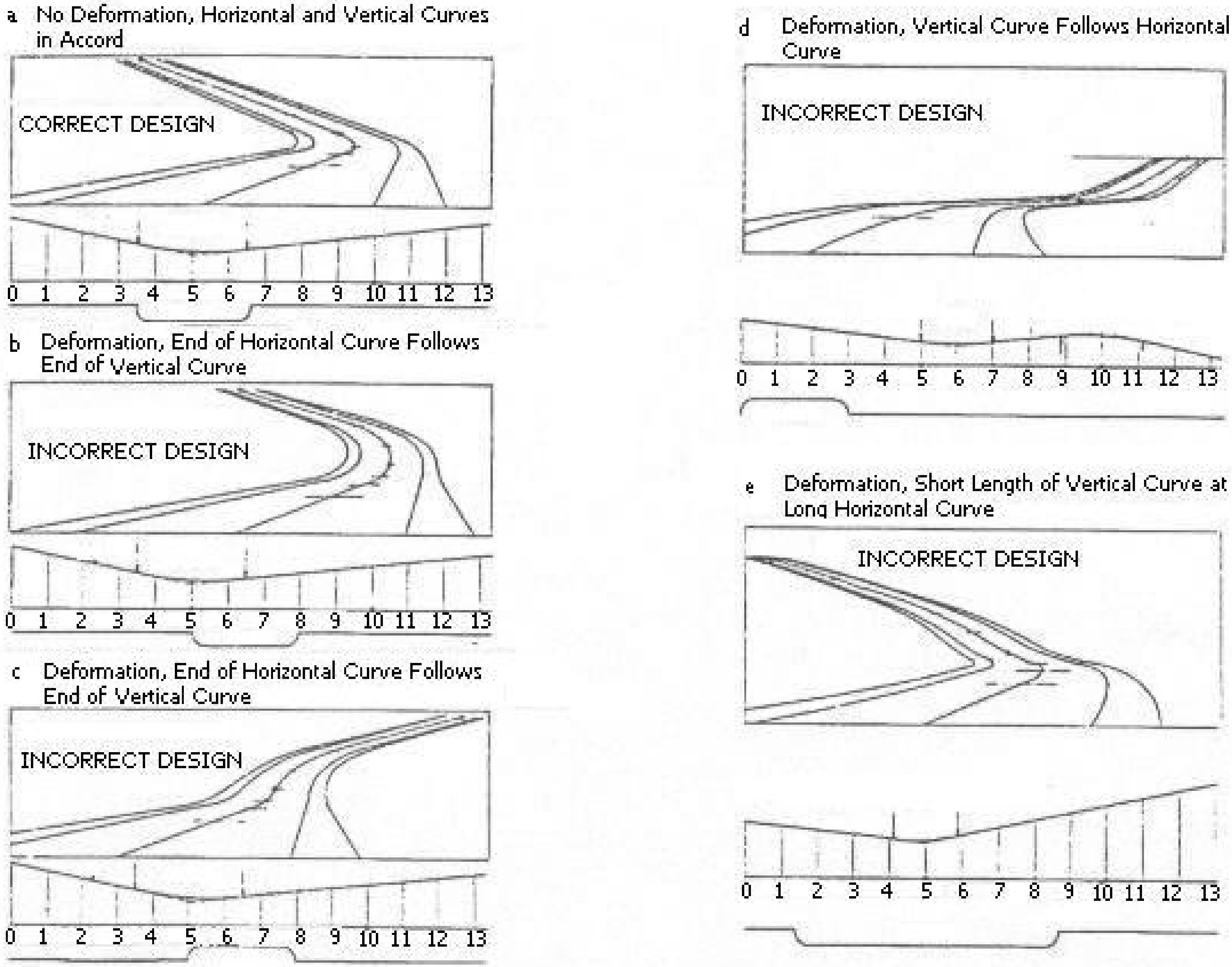
- Long curves would have a relatively flat portion near the bottom of curve
- A min. grade of 0.3% should be provided with in 15m of the level point of the curve
- Max length (drainage) is usually greater than min. length for other criteria up to 100kph and nearly equal to min length for other criteria up to 120kph

Combination of
Horizontal and Vertical Alignments

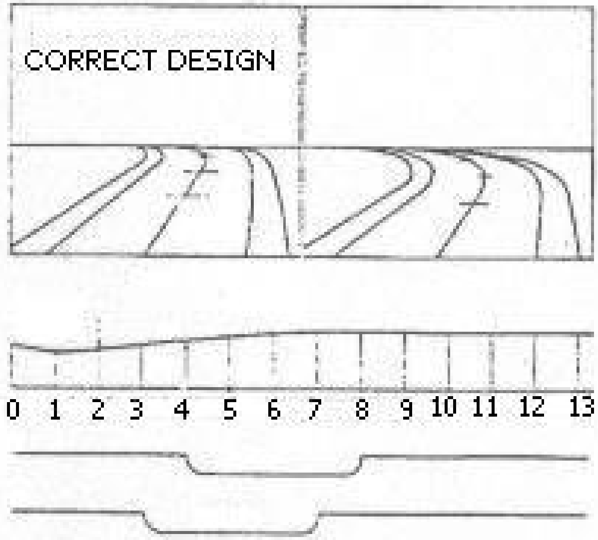
- Horizontal and Vertical Alignments should not be designed independently and should be considered together
- Correcting alignment deficiencies is extremely difficult and costly!
- *Phasing of the vertical and horizontal curves* of a road implies their coordination so that the line of the road appears to a driver to flow smoothly, avoiding the creation of hazards and visual defects. It is particularly important in the design of high-speed roads on which a driver must be able to anticipate changes in both horizontal and vertical alignment well within the safe stopping distance. It becomes more important with small radius curves than with large.
- Defects may arise if an alignment is mis-phased. Defects may be purely visual and do no more than present the driver with an aesthetically displeasing impression of the road. Such defects often occur on sag curves. When these defects are severe, they may create a psychological obstacle and cause some drivers to reduce speed unnecessarily. In other cases, the defects may endanger the safety of the user by concealing hazards on the road ahead. A sharp bend hidden by a crest curve is an example of this kind of defect.

Alignment Defects Due to Mis-phasing

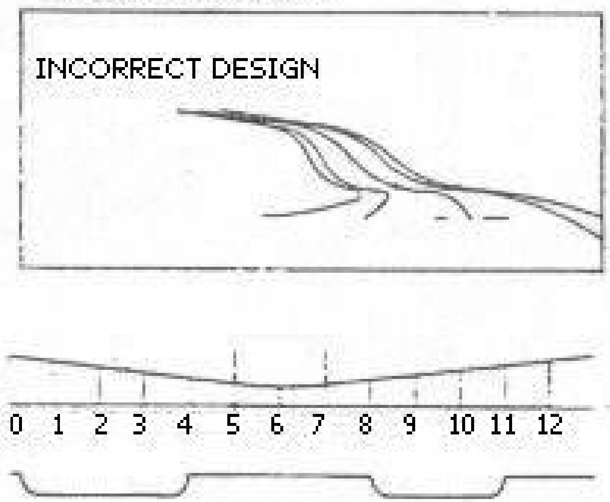
- This refers to the coordination of HA & VA so that the line of the road appears to a driver to flow smoothly, avoiding the creation of hazards and visual defects.
- Is particularly important in the design of high-speed roads on which a driver must be able to anticipate changes in both HA & VA well with in the SSD and on curves with small radius.
- Defects may arise if an alignment is mis-phased. Defects may:
  - Be purely visual
  - Create psychological obstacle and cause some drivers to reduce speed unnecessarily
  - Endanger the safety of the user by concealing hazards on the road ahead (e.g. sharp bend hidden by a crest curve)



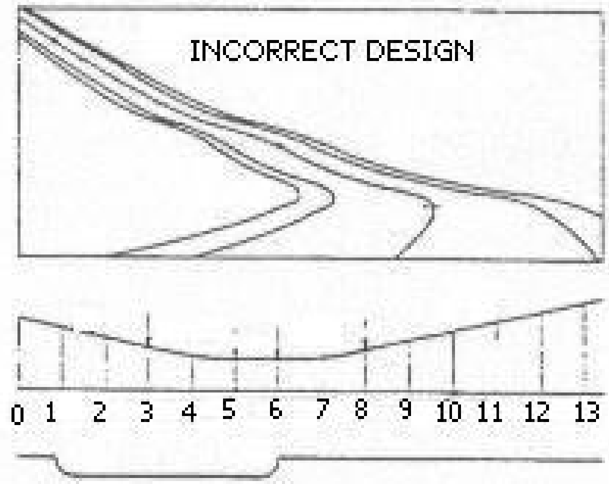
Phasing of Horizontal and Vertical Curves f No Deformation, Beginning of Horizontal Curve is before Vertical Curve



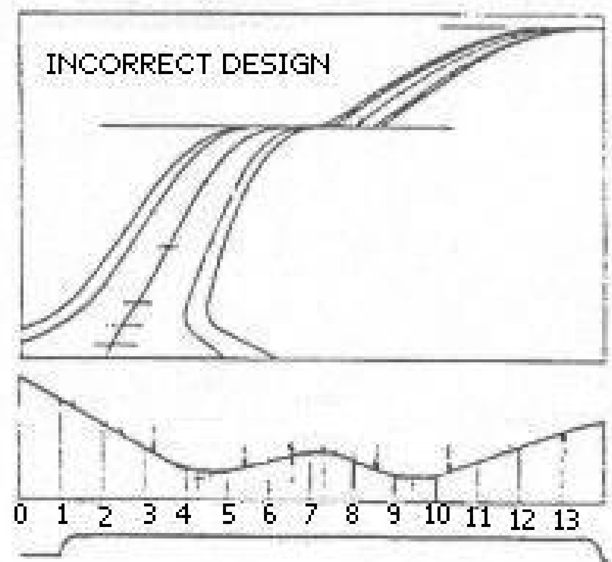
g Deformation, Sag Curve between Two Curves of the Same Direction



h Deformation, Double Sag Curves at One Horizontal Curve



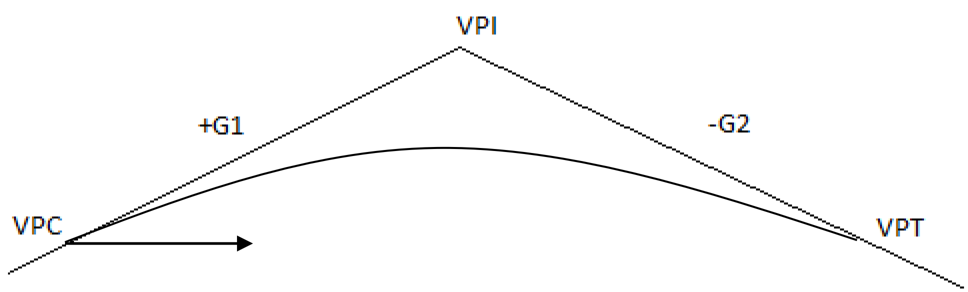
i No Phasing of Horizontal and Vertical Curves



Phasing of Horizontal and Vertical Curves

Example

A highway reconstruction project is being undertaken to reduce accident rates on the highway. The reconstruction involves a major re-alignment of the highway such that a 100kph design speed is attained. At one point on the highway, a 240m equal tangent crest vertical curve exists. Measurements show that, at 106m from the PVC, the vertical curve offset is 0.9m. Assess the adequacy of the existing curve in light of the reconstruction design speed of 100kph and, if the existing curve is inadequate, compute a satisfactory curve length.



Thank You!