GATE – CIVIL ENGINEERING

Transportation Engineering

Prof.B.Jayarami Reddy
Professor and Head
Department of Civil Engineering
Y.S.R. Engineering College of
Yogi Vemana University,
Proddatur, Y.S.R.(Dt.), A.P-516360.
E.mail : bjrcivilgate@gmail.com

TRANSPORTATION ENGINEERING

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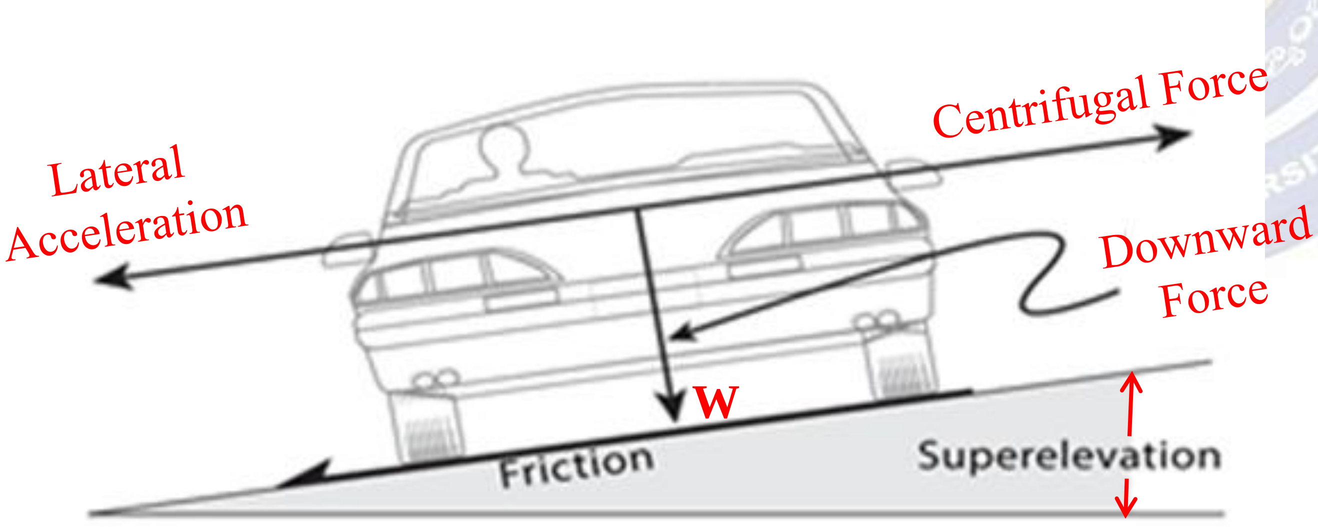
Superelevation:

- The outer edge of the pavement is raised with respect to the inner edge by providing a transverse slope throughout the length of the horizontal curve.
- The transverse inclination to the pavement surface is know as superelevation or cant or banking
- Super elevation is provided
  - i. to counteract the effect of centrifugal force
  - ii. to reduce the tendency of the vehicle to overturn or skid.



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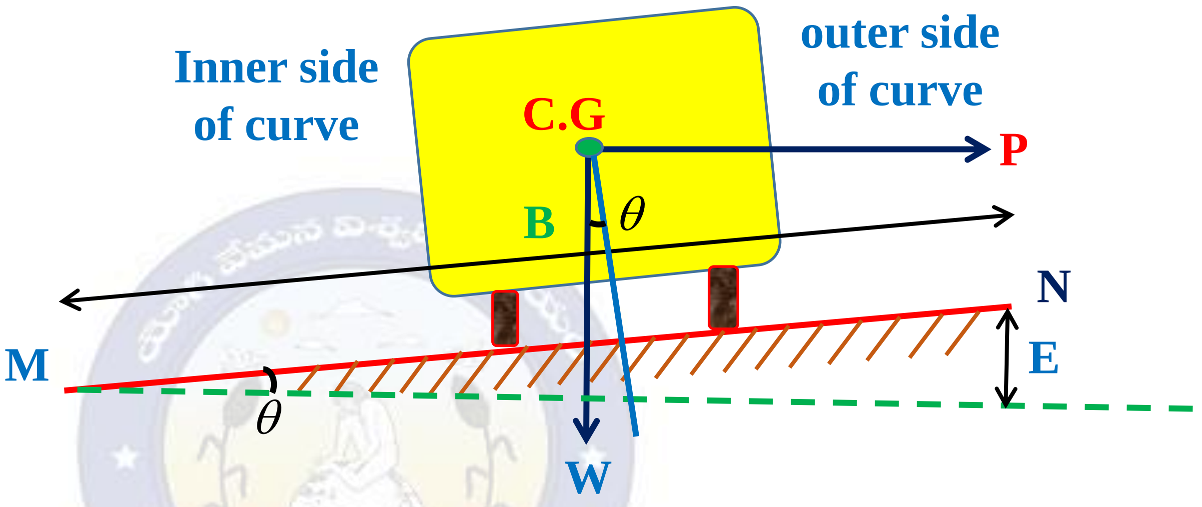
- Super elevation e is the ratio of the height of outer edge with respect to the horizontal width.



$$\tan\theta \ngtr 0.07$$

$$e = \tan\theta = \sin\theta = \frac{E}{B} = \frac{\text{Relative elevation of outer edge}}{\text{Width of pavement}}$$

$$e + f = \frac{v^2}{gR}$$

e: rate of superelevation = $\tan\theta$

f : design value of lateral friction coefficient=0.15

v : speed of the vehicle, m/sec

R : radius of the horizontal curve, m.

g : acceleration due to gravity = 9.8 m/sec^2

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$$e + f = \frac{V^2}{127R}$$

V : speed of the vehicle, kmph

If $f = 0$, Equilibrium superelevation $e = \frac{v^2}{gR} = \frac{V^2}{127R}$

For no superelevation ($e = 0$), $f = \frac{v^2}{gR} = \frac{V^2}{127R}$

Allowable speed of the vehicle, $V = \sqrt{127 f.R}$

Superelevation (e) depends on R, V, f.

For design of highway, e=0.07 and f = 0.15

0.07+0.15= $\frac{V^2}{127R}$ $\quad V = \sqrt{0.22 \times 127R}$

V: design speed decided for highway.

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Maximum allowable superelevation:

Maximum limit is necessary when the road has to cater for mixed traffic, consisting of fast and slow traffic.

- Maximum superelevation is limited to avoid the danger of toppling of loaded slow moving vehicles.
- Depends on terrain, location and environmental condition of the site.

e_{max} = 7% Plain and rolling terrains and in snow bound areas

= 10% Hill roads not bounded by a snow

= 4% Urban road stretches with frequent intersections

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Minimum superelevation:

Minimum superelevation is necessary to drain off the surface water

- If the calculated superelevation is equal to or less than the camber of the road surface, then the minimum superelevation to be provided on horizontal curve may be limited to the camber of the surface.
- After the elimination of the crown a uniform cross slope equal to the camber is maintained from outer to inner edge of pavement at the circular curve.

Superelevation design:

- For fast moving vehicles, maximum superelevation is required to counteract the centrifugal force.
- For slow moving vehicles, lower value of superelevation is enough and rely on the lateral friction.
- From practical consideration, the superelevation should be provided to fully counteract the centrifugal force due to 75% of the design speed (neglecting lateral friction developed) and limiting the maximum superelevation to 0.07 (except on hill roads)

$$e = \frac{(0.75\,v)^2}{gR} \quad \text{or} \quad e = \frac{(0.75V)^2}{127R} = \frac{V^2}{225R}$$

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Attainment of superelevation

i. Elimination of crown of the cambered section.

ii. Rotation of pavement to attain full superelevation.

- The superelevation should be attained gradually over the full length of transition curve so that the design superelevation is available at the starting point of the circular curve.
- In cases where transition curve can not be provided, two thirds of the superelevation may be obtained at the straight portion before the start of the circular curve and the balance one third at the beginning of the circular curve.
- As per IRC, the introduction of superelevation by raising the outer edge of the pavement at a rate not exceeding 1 in 150 on Plain and Rolling terrain and 1 in 60 in Mountain and Steep terrain.

The length of transition curve needed to introduced and the total superelevation E depends on i. rate of introducing superelevation

ii. The value of superelevation (E).

Length of the transition curve $= N.E$

N: Rate of introducing superelevation

The ruling minimum radius of the curve for ruling design speed v m/sec or V kmph is

$$R_{ruling} = \frac{v^2}{(e+f)g} \quad \text{or} \quad R_{ruling} = \frac{V^2}{127(e+f)} \; ; \quad R_{\min} = \frac{V'^2}{127(e+f)}$$

where V: Ruling design speed in kmph

V': Minimum design speed in kmph.

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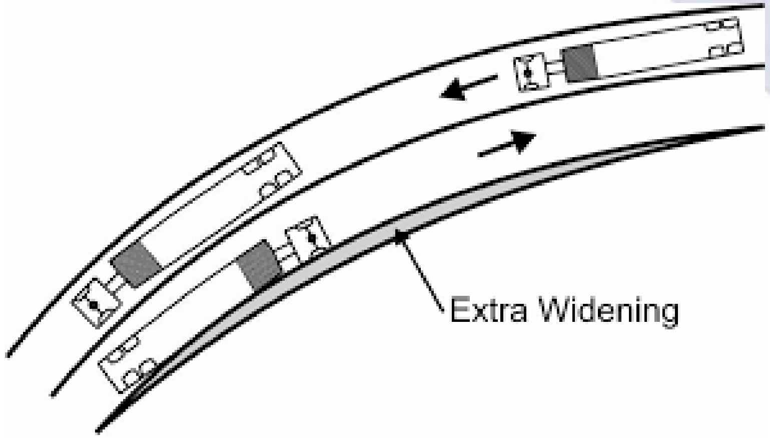
Widening of pavement on Horizontal curves

- Off tracking: When the vehicle negotiate a horizontal curve, the rear wheels do not follow the same path as that of the front wheels.
- Off tracking depends on i. length of the wheel base of the vehicle
  ii. turning angle or radius of the curve.
- Transverse skidding may occur at speeds higher than the design speed and the rear wheels may take path on the outside of those traced by the front wheels.
- The path traced by the wheels of a trailer is either side of the central path of the taking vehicle and to have a greater visibility.
- Psychological tendency to maintain a greater clearance between the vehicles.



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Extra widening of the pavement at horizontal curve (W_e) depends on

i. length of the wheel base of the vehicle, l

ii. Radius of the curve negotiated

iii. Psychological factor (depends on V and R)

- Extra width on horizontal curves will be provided when the radius is less than about 300 m.

Extra widening = Mechanical widening + Psychological widening

$$W_e = W_m + W_{ps}$$

$$W_e = \frac{nl^2}{2R} + \frac{V}{9.5\sqrt{R}}$$

n : Number of traffic lanes.

l : Length of wheel base of longest vehicle, m

= 6.0 m or 6.1 m for commercial vehicles

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V: Design speed, kmph

R: Radius of horizontal curve, m

- Extra widening is equally distributed on inner and outer sides of the curve
- On sharp curves of hill roads, the extra widening may be provided in full on inside of the curve
- In circular curves without transition curves, two-thirds the widening is provided at the end of the straight section i.e. before start of the circular curve and the remaining one third widening is provided on the circular curve beyond the tangent point.
- Widening of road is not required when the radius of curve is more than 460 m.

Horizontal transition curve

Transition curve is introduced between the straight and a circular curve in introducing gradually the designed superelevation and the extra widening.

Functions of transition curve

i. To introduce gradually the centrifugal force between the tangent point and the beginning of the circular curve avoiding a sudden jerk of the vehicle.

ii. To enable the driver turn the steering gradually for his own comfort and security.

iii. To enable gradual introduction of the designed superelevation and extra widening of pavement at the start of the circular curve.

iv. To improve the aesthetic appearance of the road

- The ideal shape of a transition curve should be such that the rate of introduction of centrifugal force or the rate of charge of centrifugal acceleration should be consistent.

- The radius of the transition curve should consistently decrease from infinity at the tangent point to the radius R of the circular curve at the end of the transition curve.

Types of transition curves

i. Spiral or Clothiod, ii. Lemniscate and iii. Cubic Parabola

Spiral curve:

- Spiral is an ideal transition curve.
- The radius is inversely proportional to the length.
- The rate of change of centrifugal acceleration is uniform throughout the length of the curve.

IRC recommends the use of spiral as transition curve because

i. The spiral curve satisfies the requirement of an ideal transition.

ii. The geometric property of spiral is such that calculations and setting out the curve in the field is simple and easy.

Length of the transition curve

i. Based on rate of change of centrifugal acceleration

$$\text{Centrifugal acceleration} = \frac{v^2}{R}$$

- Centrifugal acceleration is zero at the radius R is infinite i.e. at the start of transition curve.
- At the end of the transition, the radius R has the minimum value.
- Centrifugal acceleration is distributed over a length L_s of the transition curve.
- Larger the length of transition, lower will be the rate at which the centrifugal acceleration is introduced.

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$$L_S = \frac{v^3}{CR} = \frac{V^3}{(3.6)^3 CR} = \frac{V^3}{46.5CR} = \frac{0.0215V^3}{CR}$$

L_s : Length of the transition curve, m

C : allowable rate of change of centrifugal acceleration, m^3/sec

$$C = \frac{80}{75+V}$$ (IRC recommended) $0.5 < C < 0.8$

R: radius of the circular curve

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ii. Rate of introduction of superelevation

If the pavement is rotated about center, $L_S = \frac{EN}{2} = \frac{eN}{2}(W + W_e)$

If the pavement is rotated about the inner edge, $L_S = EN = eN(W + W_e)$

N : Rate of change of superelevation of 1in N =150 to 60

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iii. Empirical formula

For plain and Rolling terrain, $L_s = \frac{2.7V^2}{R}$

For mountainous and steep terrain, $L_s = \frac{V^2}{R}$

The length of the transition curve for the design should be the highest of the above three values.

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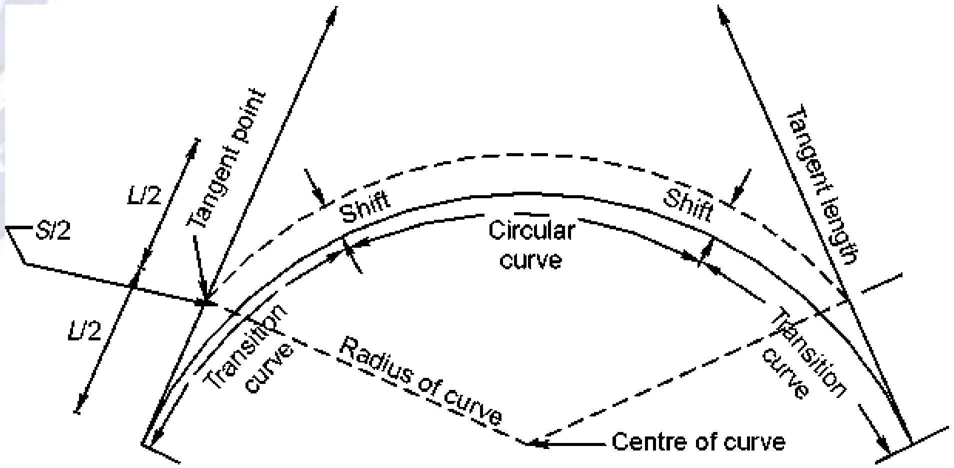
Length of the transition curve depends on

i. Radius of circular curve, R
ii. Design speed, V
iii. Allowable rate of change of centrifugal acceleration, C
iv. Maximum amount of superelevation, E.
v. Rotation of the cross section of pavement about the inner edge or centre line.
vi. Allowable rate of introduction of superelevation.

Shift of the transition curve :

For the main circular curve to fit in the transition curve, which is laid in the shape of a cubic parabola, it is required be moved inward by a measure known as the 'shift'

$$S = \frac{L_s^2}{24R}$$



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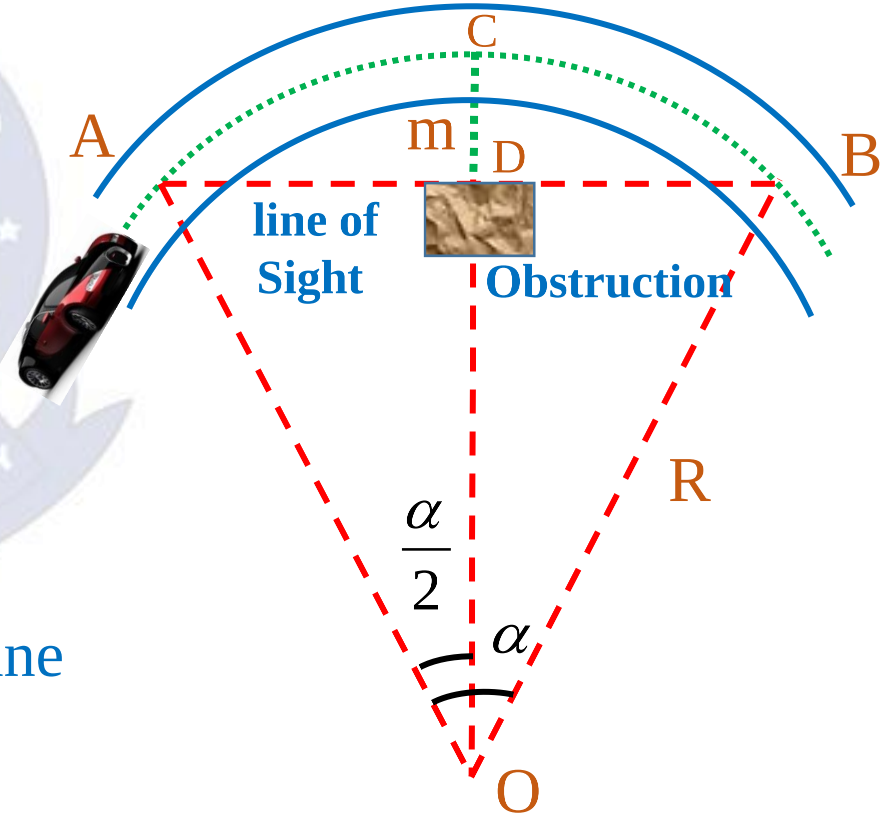
Set-back distance

- Set-back distance or clearance distance is the distance from the centre line of a horizontal curve to an obstruction on the inner side of the curve.
- To provide adequate sight distance.
- Set-back distance depends on
  - i. Required sight distance, S
  - ii. Radius of horizontal curve, R
  - iii. Length of the curve, $L\left(L > S \text{ or } L < S\right)$



For Single Lane

i. $L > S$

Set-back distance, m = CD

= OC – OD

$$m = R - R\cos\frac{\alpha}{2} \quad \text{for single lane}$$

$$Sin\frac{\alpha}{2} = \frac{BD}{OB} \Rightarrow \frac{\alpha}{2} = \frac{S}{2R} \Rightarrow \frac{\alpha}{2} = \frac{180}{\pi}\frac{S}{2R}$$

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For single lane

ii. $L < S$

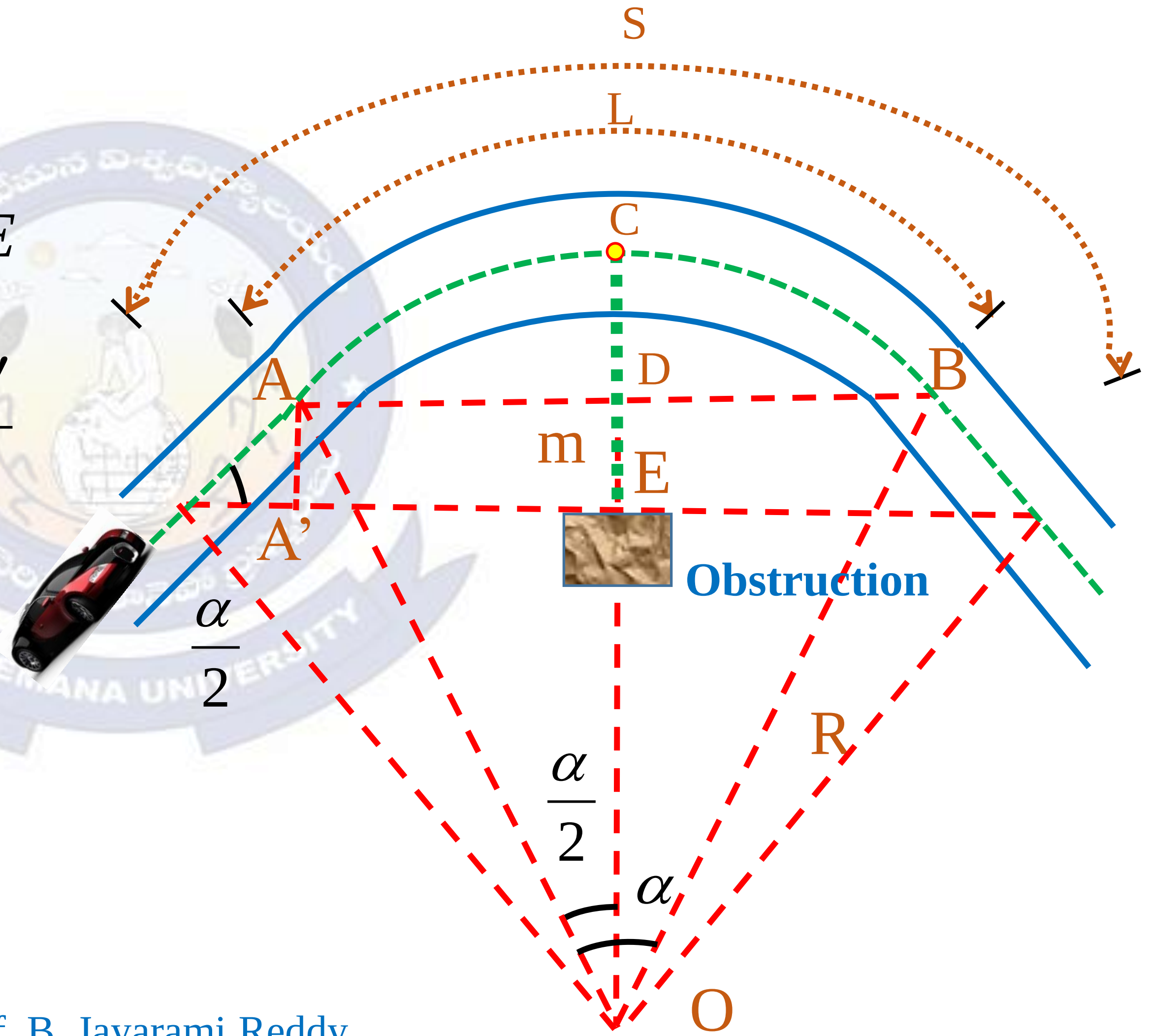
Setback distance, $m' = CE$

$$= CD + DE$$

$$= (OC - OD) + DE$$

$$m' = R\left(1 - \cos\frac{\alpha'}{2}\right) + \frac{(S-L)}{2}\sin\frac{\alpha'}{2}$$

$$\frac{\alpha'}{2} = \frac{AD}{OA} \Rightarrow \frac{\alpha'}{2} = \frac{L}{2R} \Rightarrow \frac{\alpha'}{2} = \frac{180}{\pi}\frac{L}{2R}$$



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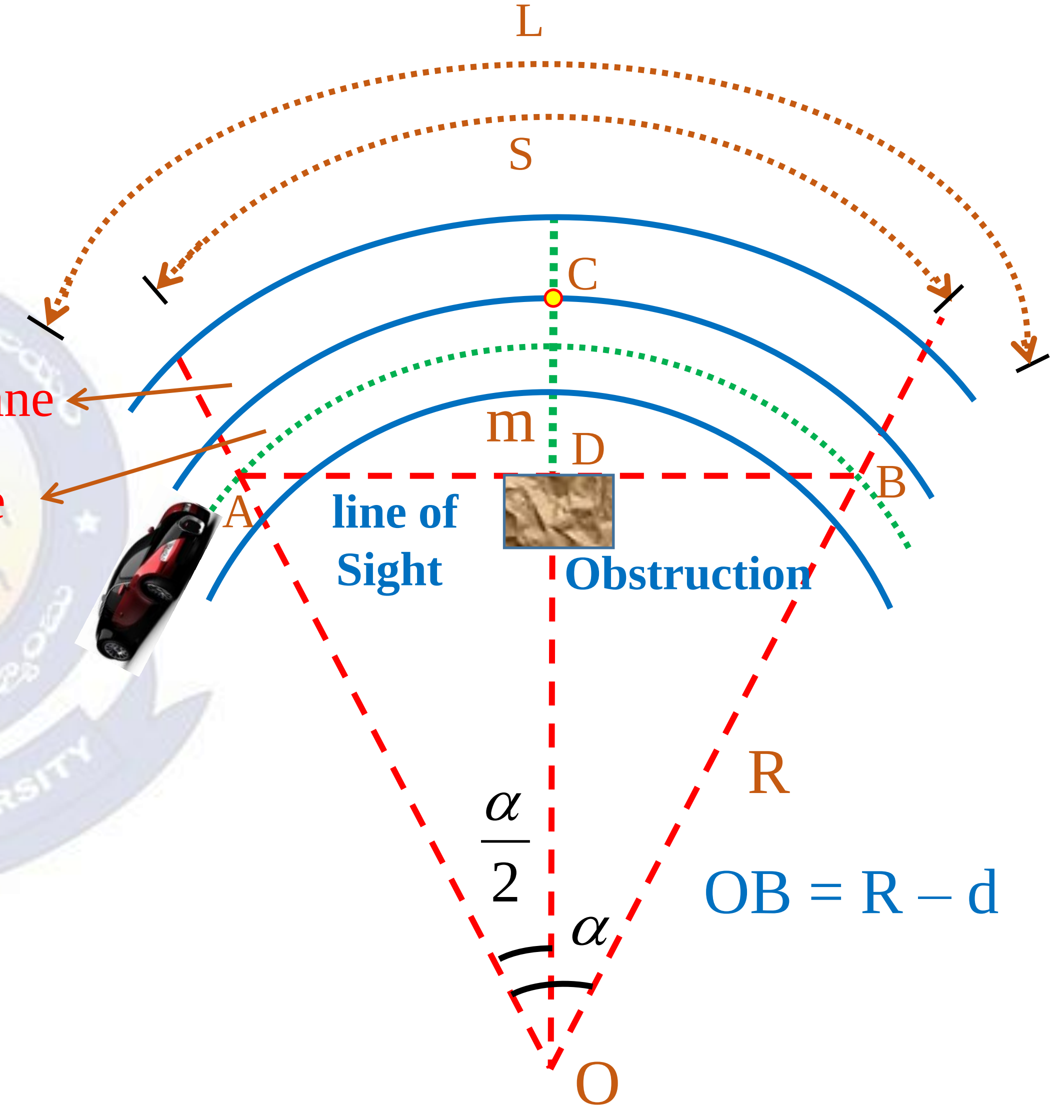
For two or more lanes

i. $L > S$

Setback distance , m = CD

= OC – OD

$$m = R - (R-d)\cos\frac{\alpha}{2}$$



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For two or more lanes

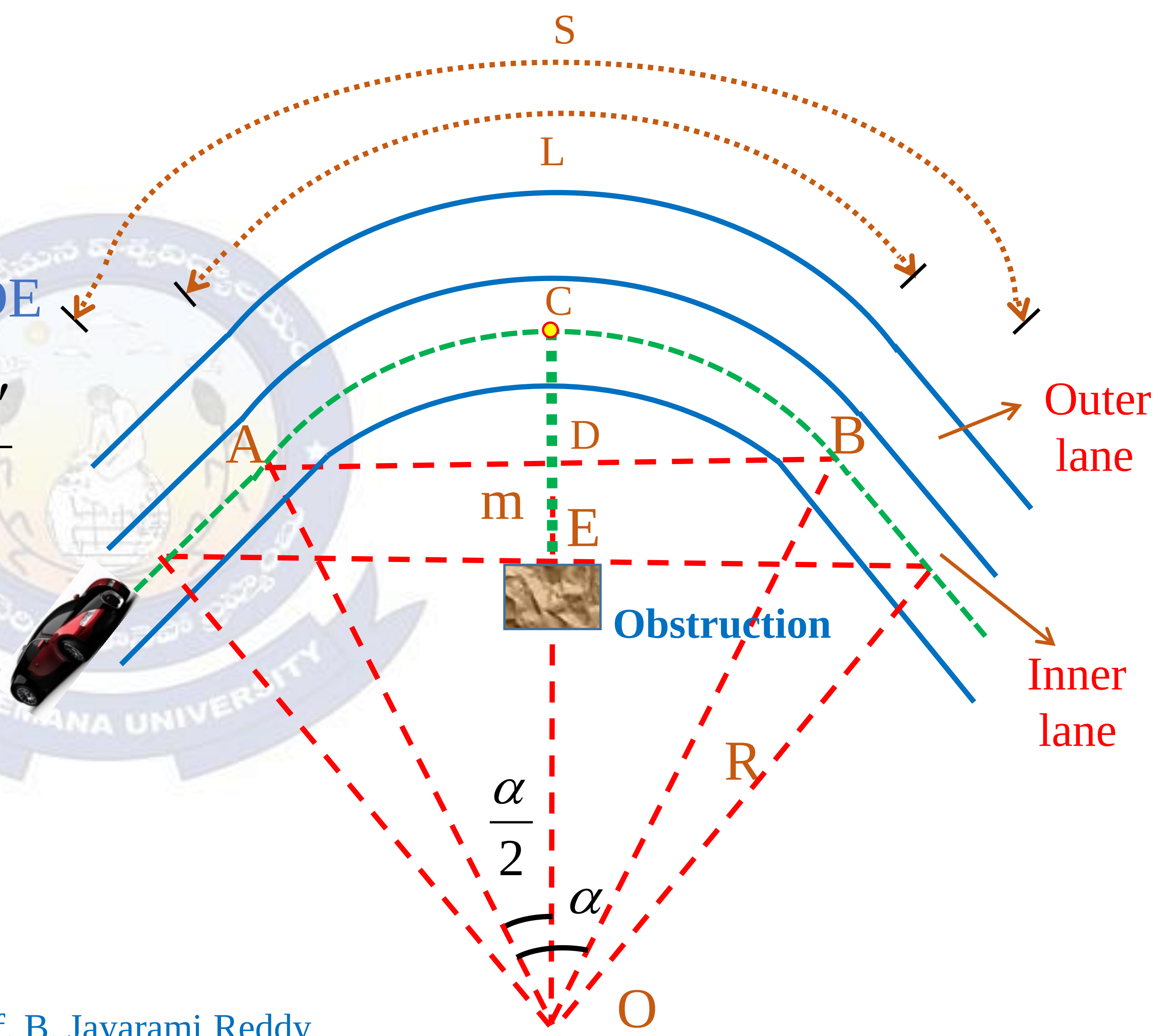
ii. $L < S$

Setback distance , m' = CE

= CD + DE

= (OC – OD) + DE

$$m' = R - (R-d)\cos\frac{\alpha'}{2} + \frac{(S-L)}{2}\sin\frac{\alpha'}{2}$$



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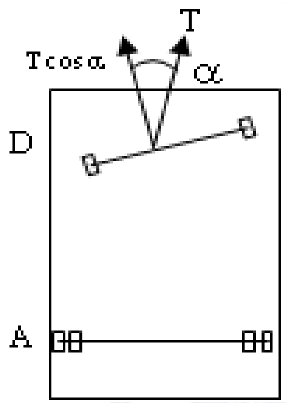
Curve Resistance:

Curve resistance is the loss of tractive force due to turning of a vehicle on a horizontal curve.



Curve resistance = $T - T\cos\alpha = T(1-\cos\alpha)$

T : Actual tractive force.

- Curve resistance depends on the turning angle α.
- Turning along the horizontal curve is effected due to the lateral friction developed between the front wheels and the pavement.

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Design of vertical alignment

The vertical alignment consists of grades and vertical curves, and it influences the vehicle speed, acceleration, deceleration, stopping distance, sight distance and comfort in vehicle movements at high speeds.

Gradient: Gradient is the rate of rise or fall along the length of the road with respect to the horizontal.

- expressed as a ratio 1 in x or $\frac{100}{x}\%$ (1 vertical to x horizontal), n i.e. n in 100

  α : Angle of gradient , $Tan\,\alpha = n\%$
- Ascending gradients are +ve and are denoted as $+n_1, +n_2$ etc and the descending gradients are - ve and are denoted as $-n_3, -n_4$ etc.
- Deviation angle (N) is the angle measures the change of direction at the intersection of two grades.

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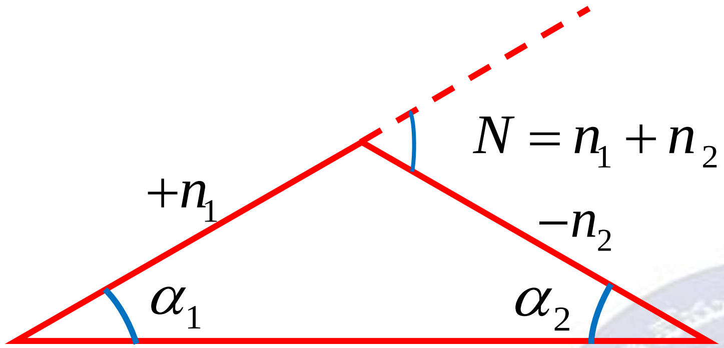

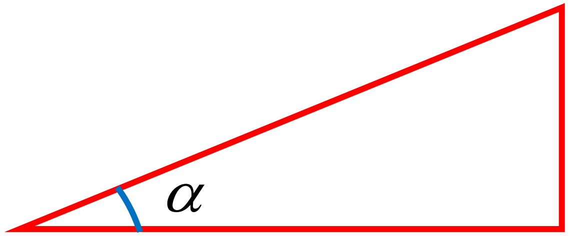

Gradient = 1 in x = tan α = $n = \frac{100}{x}\%$

Very steep gradients are avoided because

i. difficult to climb the grade

ii. increase in operational cost of the vehicle.

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- **Ruling gradient** or Design gradient is the maximum gradient within which the designer attempts to design the vertical profile of a road.
- **Limiting gradients** are used in a place having steeper gradients than ruling gradient.
- **Exceptional gradient** is the steeper gradient at extra ordinary situations
  - used for short stretches not exceeding about 100 m.
- **Critical length of grade** for a design is the maximum length of ascending gradient which a loaded truck can operate without undue reduction in speed.

Gradients for roads in different terrains

Terrain	Ruling,%	Limiting,%	Exceptional,%
Plain or Rolling	3.3% (1in 30)	5 (1 in 20)	6.7 (1 in 15)
Mountainous or Steep terrain (above 3000 m MSL)	5 (1 in 20)	6 (1 in 16.7)	7 (1 in 14.3)
Steep terrain upto 3000 m MSL.	6 (1 in16.7)	7 (1 in 14.3)	8 (1 in 12.5)

- Minimum gradient is to be provided for roads from the drainage point of view.
- Minimum gradient depends on rainfall, run off, type of soil, Topology and other site conditions.

Grade compensation

Grade compensation is the reduction in gradient at the horizontal curve.

Grade compensation, Percent = $\frac{30+R}{R}$, subject to a maximum value of $\frac{75}{R}$.

As per IRC, the grade compensation is not necessary for gradients flatter than 4.0%.

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Vertical curves:

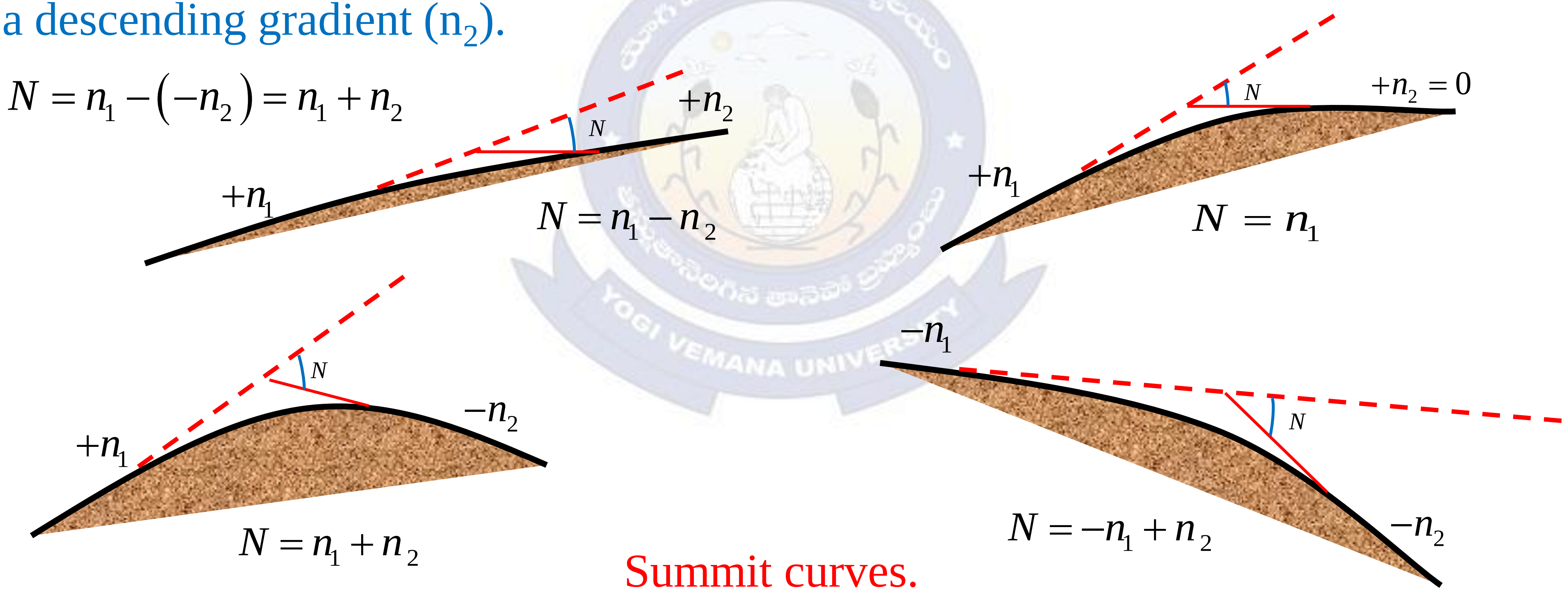
i. Summit curves or Crest curves with convexity upwards.

ii. Valley or Sag curves with concavity upwards.

Vertical curves

i. Summit curves:

- The deviation angle between the two intersecting gradients is equal to the algebraic difference between them.
- Maximum deviation angle (N) occurs when an ascending gradient (n_1) meets with a descending gradient (n_2).



Summit curves.

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- Providing adequate sight distance is a problem in designing summit curves.
- Circular summit curve is ideal as the sight distance available throughout the length of Circular curve is constant.
- Simple parabola summit curve will give good riding comfort.
- Easy for arithmetical manipulation for computing ordinates.
- In practice, simple parabolic curve is used as summit curve.
- When a fast moving vehicle travels along a summit curve, the centrifugal force will act upwards, against gravity and hence a part of the pressure on the tyres and spring of the vehicle suspensions is relieved. So there will not be any discomfort to passengers on summit curves.
- To avoid accidents, it is essential to provide sight distance at least equal to the stopping distance at all points.

Length of summit curve

Equation of parabola, $y = ax^2$, where $a = \frac{N}{2L}$.

N : deviation angle.

L : length of the curve.

For SSD

i. L > SSD, when the length of the curve is greater than the stopping sight distance

$$L = \frac{NS^2}{\left(\sqrt{2H} + \sqrt{2h}\right)^2} \qquad L = \frac{NS^2}{4.4}$$

L: Length of summit curve, m

S: Stopping sight distance SSD, m

N: Deviation angle, radians

H : height of eye level of driver above roadway surface = 1.2 m

h : height of object above the pavement surface= 0.15 m

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ii. L< SSD, when the length of curve is less than the stopping sight distance

$$L = 2S - \frac{\left(\sqrt{2H} + \sqrt{2h}\right)^2}{N} \qquad L = 2S - \frac{4.4}{N}$$

Minimum radius of the parabolic summit curve, $R = \frac{L}{N}$.

For OSD or ISD H=h=1.2m

i. When L >S ; $L = \frac{NS^2}{8H}$; $L = \frac{NS^2}{9.6}$

ii. When L< S ; $L = 2S - \frac{8H}{N}$; $L = 2S - \frac{9.6}{N}$

- When deviation angle is small, the length of summit curve generally works out less than the sight distance.
- In very small deviation angles, the length required sometimes works out as a negative value indicating that there is no problem of sight restriction at the summit curve.
- The distance of highest point on the summit curve from the tangent point on the first grade n_1 is $\frac{L.n_2}{N}$.

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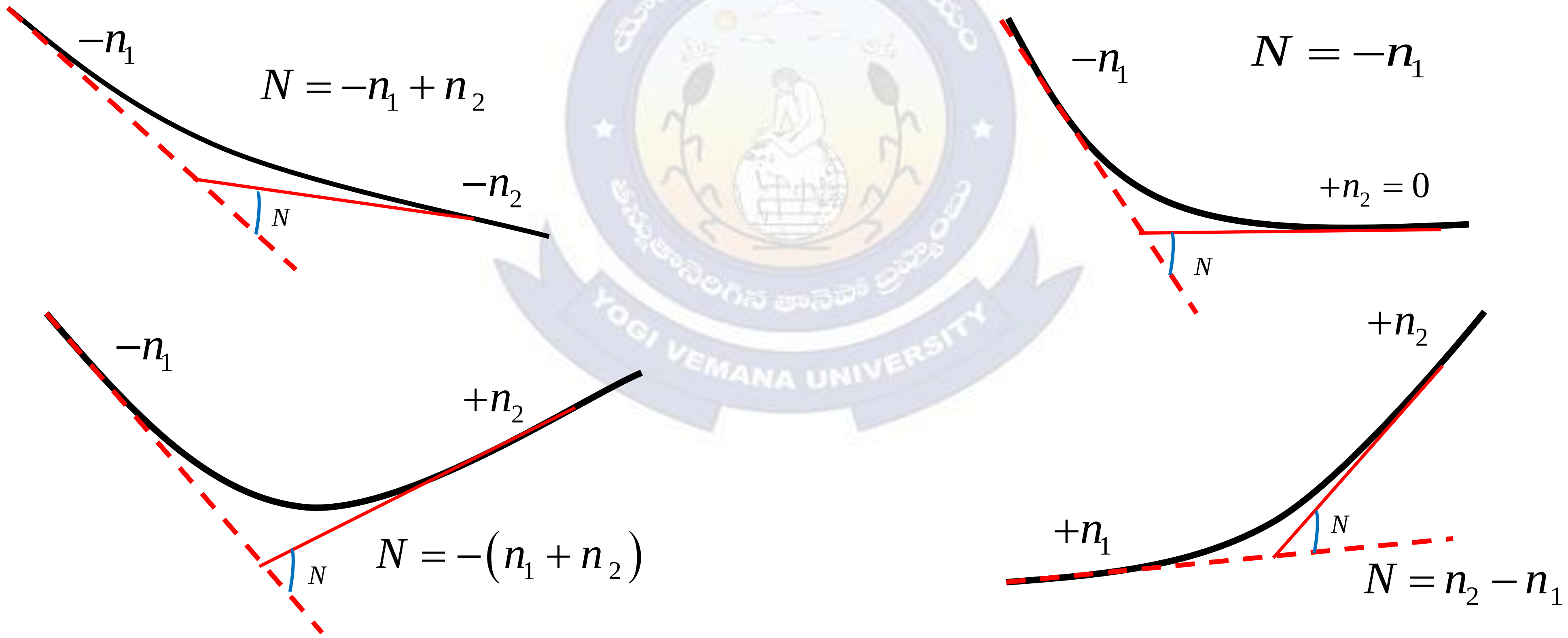
Valley curves (or Sag curves)

- Maximum possible deviation angle is obtained when a descending gradient meets with an ascending gradient.
- In valley curves, sight distance is not a problem during day light.
- Sight distance decreased during night driving under head lights of vehicles.
- Factors considered in the design of valley curve are
  i. impact free movement of vehicles at design speed or the comfort to the passengers
  ii. availability of stopping sight distance under head lights of vehicles for night driving (head light sight distance)
- At the valley curve, the centrifugal force acts downwards adding to the pressure on the springs and suspensions of the vehicle in addition to that due to the weight of the vehicle.
- Allowable rate of change of centrifugal acceleration govern the design of valley curves.
- Best shape of valley curve is transition curve.

- Cubic parabola is generally preferred in vertical valley curves.
- Head light sight distance available at valley curves should be at least equal to the stopping sight distance.
- No problem for overtaking sight distance during night as other vehicles with head
- lights can be seen from a considerable distance.



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Length of valley curve depends on

i. The allowable rate of change of centrifugal acceleration of 0.6 m/sec^3.

ii. Head light sight distance.

Head light sight distance governs the design.

i. for comfort condition

$$L_s = \frac{v^3}{CR} \;; \qquad L = 2L_s$$

L_s: Length of the transition curve = $L = 2\left[\frac{Nv^3}{C}\right]^{1/2}$; $L = 0.38\left(NV^3\right)^{1/2}$

L : Total length of valley curve

N : Deviation angle in radians

V : Design speed, kmph.

Minimum radius of the valley curve for cubic parabola, $R = \frac{L_s}{N} = \frac{L}{2N}$.

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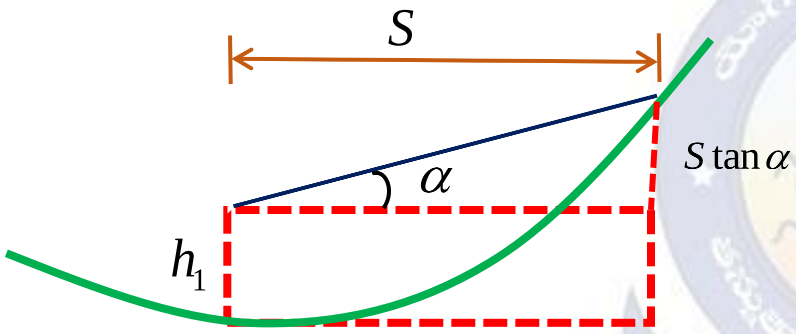
ii. For head light sight distance

a. L>SSD



$$L = \frac{NS^2}{(2h_1 + 2S\tan\alpha)}$$

h_1 =0.75m, $\alpha = 1°$; $$L = \frac{NS^2}{(1.5 + 0.035\,S)}$$

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b. L<SSD

$$L = 2S - \frac{(2h_1 + 2S\tan\alpha)}{N}$$

$h_1 = 0.75$, $\alpha = 1°$; $$L = 2S - \frac{(1.5 + 0.035\,S)}{N}$$

- If the gradients on either side are equal, the lowest point on the valley curve will be on the bisector of the angle between the grades.
- When the gradients are not equal, the lowest point lies on the side of flatter grade.
- The distance of lowest point from the tangent point of the first grade n_1 is

$$x_0 = L\sqrt{\frac{n_1}{2N}}$$

$$SD = v.t + \frac{v^2}{2g\,f}, \quad v \text{ is in m/s} \qquad SD = 0.278\,V.t + \frac{V^2}{254\,f}, \quad V \text{ is in Km/h}$$

$$SD = v.t + \frac{v^2}{2g(f \pm 0.01n)} \qquad SD = 0.278Vt + \frac{V^2}{254(f \pm 0.01n)}$$

$$OSD = d_1 + d_2 + d_3$$

$$OSD = v_b.t + (v_b.T + 2s) + v.T$$

$$f < \frac{b}{2h}$$ Skidding occurs

$$T = \sqrt{\frac{4s}{a}} \qquad s = 0.7\,v_b + 6$$

$$f > \frac{b}{2h}$$ Overturning occurs

$$OSD = 0.278V_b.t + 0.278V_b.T + 0.278V.T \qquad T = \sqrt{\frac{4 \times 3.6S}{A}} = \sqrt{\frac{14.4S}{A}}$$

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$$e+f=\frac{v^2}{gR}$$

$$e+f=\frac{V^2}{127R}$$

$$e=\frac{V^2}{225R}$$

$$W_e=\frac{nl^2}{2R}+\frac{V}{9.5\sqrt{R}}$$

$$S=\frac{L_s^2}{24R}$$

$$L_s=\frac{2.7V^2}{R}$$

$$L_s=\frac{V^2}{R}$$

$$L_S=\frac{v^3}{CR}$$

$$L_s=\frac{0.0215V^3}{CR}$$

$$C=\frac{80}{75+V}$$

$$L_S=\frac{EN}{2}=\frac{eN}{2}(W+W_e)$$

$$L_S=EN=eN(W+W_e)$$

$$m=R-R\cos\frac{\alpha}{2}$$

$$SD=v.t+\frac{v^2}{2g(f\ \pm 0.01n)}$$

$$\frac{30+R}{R}$$

$$m'=R-(R-d)\cos\frac{\alpha'}{2}+\frac{(S-L)}{2}\sin\frac{\alpha'}{2}$$

$$L=\frac{NS^2}{\left(\sqrt{2H}+\sqrt{2h}\right)^2}$$

$$L=\frac{NS^2}{4.4}$$

$$\frac{75}{R}$$

$$m=R-(R-d)\cos\frac{\alpha}{2}$$

$$L=2S-\frac{\left(\sqrt{2H}+\sqrt{2h}\right)^2}{N}$$

$$L=2S-\frac{4.4}{N}$$

$$m'=R\left(1-\cos\frac{\alpha'}{2}\right)+\frac{(S-L)}{2}\sin\frac{\alpha'}{2}$$

$$L=\frac{NS^2}{9.6}$$

$$L=2S-\frac{9.6}{N}$$

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