UNIT -2

IMPORTANCE OF GEOMETRIC DESIGN

The geometric design of a highway deal with the dimensions and layout of visible features of the highway such as alignment, sight distances and intersections.

The geometrics of highway should be designed to provide optimum efficiency in traffic operations with maximum safety at reasonable cost. The designer may be exposed to either planning of new highway net work or improvement of existing highways to meet the requirements of the existing and the anticipated traffic.

It is possible to design and construct the pavement of a road in stages; but it is very expensive and rather difficult to improve the geometric elements of a road in staged at a later date.

Geometric design of highways deals with following elements:

(i) Cross section elements
(ii) Sight distance considerations
(iii) Horizontal alignment details
(iv) Vertical alignment details
(v) Intersection elements

DESIGN CONTROLS AND CRITERIA

The geometric design of highways depends on several design factors. The important of these factors which control the geometric elements are :

(i) Design speed
(ii) Topography
(iii) Traffic factors
(iv) Design hourly volume and capacity
(v) Environmental and other factors.

(I) DESIGN SPEED

The design speed is the most important factor controlling the geometric design elements of highways. In India different speed standards have been assigned depending upon the importance or the class of the road such as National/State Highways, Major/Other District Road and Village Roads. Further the design speed standards are modified depending upon the terrain or topography. Similarly urban roads have a different set of design speeds.

(II) TOPOGRAPHY

The topography or the terrain conditions influence the geometric design of highway significantly. The terrains are classified based on the general slope of the country across the alignment, as plain rolling, mountainous and steep terrains. The design standards specified for different classed of roads are different depending on the terrain classification. For example the design or ruling speed of NH and SH on plain terrain with general cross slope up to 10% is 100 kmph whereas the speed on rolling terrain with general cross slope of 10 to 25% is 80 kmph and that on mountainous terrain with cross slope 25 to 60% is 50 kmph.

(III) TRAFFIC FACTORS

The factors associated with the traffic that affect geometric design of roads are the vehicular characteristics and human characteristics of road users. It is difficult to decide the design vehicle or the standard traffic lane under the mixed traffic flow condition prevalent especially on urban roads of developing countries. This is a complex problem. The different vehicle classes such as passenger cars, buses, trucks, motor cycles, etc. have different speed and acceleration characteristics, apart from having different dimensions and weights.

(IV) DESIGN HOURLY VOLUME AND CAPACITY

The traffic flow or volume keeps fluctuating with time, from a low value during off-peak hours to the highest value during the peak hour. It will be uneconomical to design the roadway facilities for the peak traffic flow or the highest hourly traffic volume.

(V) ENVIRONMENTAL AND OTHER FACTORS

The environmental factors such as aesthetics, landscaping, air pollution, noise pollution and other local conditions should be given due consideration in the design on road geometrics.

Cross sectional elements

The features of the cross-section of the pavement influence the life of the pavement as well as the riding comfort and safety. The characteristics of cross-sectional elements are important in highway geometric design because they influence the safety and comfort. Camber provides for drainage, frictional resistance and reflectivity for safety etc. The road elements such as kerb, shoulders, carriageway width etc. should be adequate enough for smooth, safe and efficient movement of traffic. IRC has recommended the minimum values for all these cross-sectional elements.

1. **Pavement surface characteristics:** For safe and comfortable driving four aspects of the pavement surface are important; the friction between the wheels and the pavement surface, smoothness of the road surface, the light reflection characteristics of the top of pavement surface, and drainage to water.

a) **Friction:** Friction between the wheel and the pavement surface is a crucial factor in the design of horizontal curves and thus the safe operating speed. Further, it also affects the acceleration and deceleration ability of vehicles. Lack of adequate friction can cause skidding or slipping of vehicles. Skidding happens when the path traveled along the road surface is more than the circumferential movement of the wheels due to friction Slip occurs when the wheel revolves more than the corresponding longitudinal movement along the road.

Various factors that affect friction are:

- Type of the pavement (like bituminous, concrete, or gravel),
- Condition of the pavement (dry or wet, hot or cold, etc),
- Condition of the tyre (new or old), and
- Speed and load of the vehicle.
- The frictional force that develops between the wheel and the pavement is the load acting multiplied by a factor called the coefficient of friction and denoted as ***f***. The choice of the value of ***f*** is a very complicated issue since it depends on many variables. IRC suggests the coefficient of longitudinal friction as 0.35-0.4 for design of stopping sight distance. For the design of horizontal curves lateral coefficient of friction is 0.15.

b) **Unevenness:** It is always desirable to have an even surface, but it is not possible to have such a one. Even if a road is constructed with high quality pavers, it is possible to develop unevenness due to pavement failures. Unevenness affects the vehicle operating cost, speed, riding comfort, safety, fuel consumption and wear and tear of tyres.
Unevenness index is a measure of unevenness which is the cumulative measure of vertical undulations of the pavement surface recorded per unit horizontal length of the road. An unevenness index value less than 150 cm/km is considered as good, a value less than 250 cm/km is satisfactory up to speed of 100 kmph and values greater than 320 cm/km is considered as uncomfortable even for 50 kmph.

C) **Light reflection:** White roads have good visibility at night, but caused glare during day time. Black roads has no glare during day, but has poor visibility at night Concrete roads has better visibility and less glare It is necessary that the road surface should be visible at night and reflection of light is the factor that answers it.

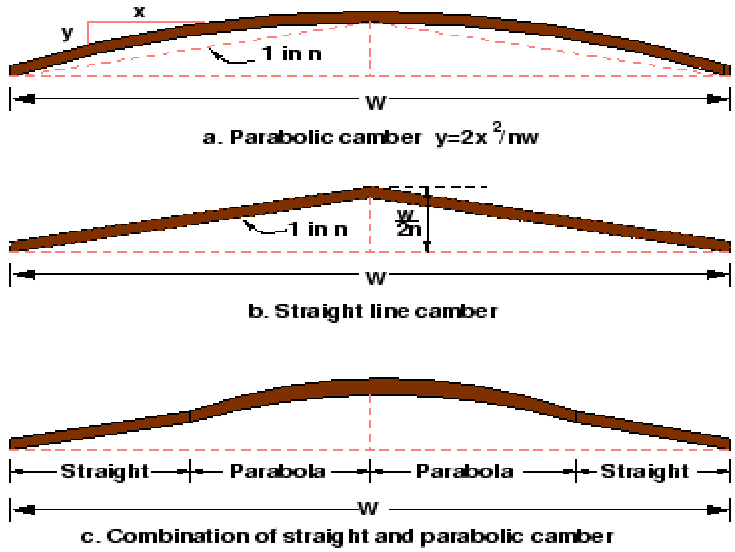
D) **Drainage:**
The pavement surface should be absolutely impermeable to prevent seepage of water into the pavement layers. Further, both the geometry and texture of pavement surface should help in draining out the water from the surface in less time.

2. Camber

Camber or cant is the cross slope provided to raise middle of the road surface in the transverse direction to drain off rain water from road surface. The objectives of providing camber are:

- Surface protection especially for gravel and bituminous roads
- Sub-grade protection by proper drainage
- Quick drying of pavement which in turn increases safety

Too steep slope is undesirable for it will erode the surface. Camber is measured in 1 in n or n% (Eg. 1 in 50 or 2%) and the value depends on the type of pavement surface. The values suggested by IRC for various categories of pavement are given in Table 1. The common types of camber are parabolic, straight, or combination of them (Figure 1)



Different types of camber

IRC Values for camber		
Surface Type	**Heavy Rain**	**Light Rain**
Cement concrete	**(1 in 50) 2 %**	**(1 in 60) 1.7 %**
Thin bituminous surface	**(1 in 40) 2.5 %**	**(1 in 50) 2 %**
WBM and gravel pavement	**(1 in 33) 3 %**	**(1 in 40) 2.5 %**
Earthen roads	**(1 in 25) 4 %**	**(1 in 33) 3 %**

3. Width of carriage way

Width of the carriage way or the width of the pavement depends on the width of the traffic lane and number of lanes. Width of a traffic lane depends on the width of the vehicle and the clearance. Side clearance improves operating speed and safety. The maximum permissible width of a vehicle is 2.44 and the desirable side clearance for single lane traffic is 0.68 m. This require minimum of lane width of 3.75 m for a single lane road (Figure 1a). However, the side clearance required is about 0.53

m, on either side and 1.06 m in the center. Therefore, a two lane road require minimum of 3.5 meter for each lane (Figure 1b). The desirable carriage way width recommended by IRC is given in Table 1

Table 1: IRC Specification for carriage way width

Single lane	**3.75**
Two lane, no kerbs	**7.0**
Two lane, raised kerbs	**7.5**
Intermediate carriage	**5.5**
Multi-lane	**3.5**

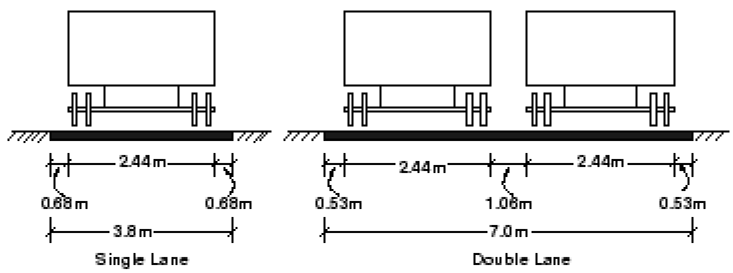


Figure 1: Lane width for single and two lane roads

4. Kerbs

Kerbs indicate the boundary between the carriage way and the shoulder or islands or footpaths. Different types of kerbs are (Figure 1):

Low or mountable kerbs : This type of kerbs are provided such that they encourage the traffic to remain in the through traffic lanes and also allow the driver to enter the shoulder area with little difficulty. The height of this kerb is about 10 cm above the pavement edge with a slope which allows the vehicle to climb easily. This is usually provided at medians and channelization schemes and also helps in longitudinal drainage.

Semi-barrier type kerbs : When the pedestrian traffic is high, these kerbs are provided. Their height is 15 cm above the pavement edge. This type of kerb prevents encroachment of parking vehicles, but at acute emergency it is possible to drive over this kerb with some difficulty.

Barrier type kerbs : They are designed to discourage vehicles from leaving the pavement. They are provided when there is considerable amount of pedestrian traffic. They are placed at a height of 20 cm above the pavement edge with a steep batter.

Submerged kerbs : They are used in rural roads. The kerbs are provided at pavement edges between the pavement edge and shoulders. They provide lateral confinement and stability to the pavement.

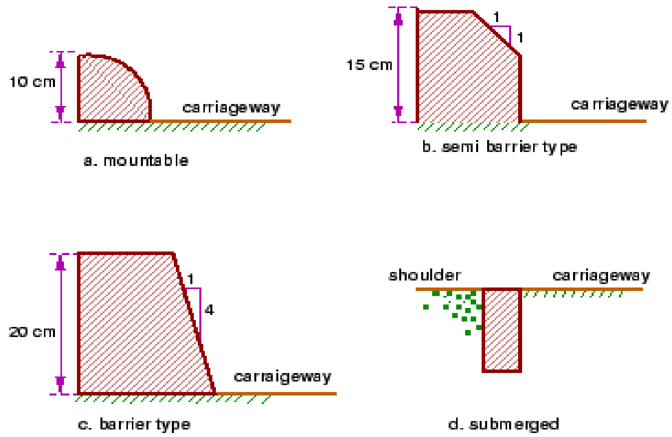


Figure 1: Different types of kerbs

5. **Road margins:** The portion of the road beyond the carriageway and on the roadway can be generally called road margin. Various elements that form the road margins are given below.

Shoulders: Shoulders are provided along the road edge and is intended for accommodation of stopped vehicles, serve as an emergency lane for vehicles and provide lateral support for base and surface courses. The shoulder should be strong enough to bear the weight of a fully loaded truck even in wet conditions. The shoulder width should be adequate for giving working space around a stopped vehicle. It is desirable to have a width of 4.6 m for the shoulders. A minimum width of 2.5 m is recommended for 2-lane rural highways in India.

Parking lanes: Parking lanes are provided in urban lanes for side parking. Parallel parking is preferred because it is safe for the vehicles moving on the road. The parking lane should have a minimum of 3.0 m width in the case of parallel parking.

Bus-bays: Bus bays are provided by recessing the kerbs for bus stops. They are provided so that they do not obstruct the movement of vehicles in the carriage way. They should be at least 75 meters away from the intersection so that the traffic near the intersections is not affected by the bus-bay.

Service roads: Service roads or frontage roads give access to access controlled highways like freeways and expressways. They run parallel to the highway and will be usually isolated by a separator and access to the highway will be provided only at selected points. These roads are provided to avoid congestion in the expressways and also the speed of the traffic in those lanes is not reduced.

Cycle track: Cycle tracks are provided in urban areas when the volume of cycle traffic is high Minimum width of 2 meter is required, which may be increased by 1 meter for every additional track.

Footpath: Footpaths are exclusive right of way to pedestrians, especially in urban areas. They are provided for the safety of the pedestrians when both the pedestrian traffic and vehicular traffic is high.

Minimum width is 1.5 meter and may be increased based on the traffic. The footpath should be either as smooth as the pavement or smoother than that to induce the pedestrian to use the footpath.

Guard rails: They are provided at the edge of the shoulder usually when the road is on an embankment. They serve to prevent the vehicles from running off the embankment, especially when the height of the fill exceeds 3 m. various designs of guard rails are there. Guard stones painted in alternate black and white are usually used. They also give better visibility of curves at night under headlights of vehicles.

6. Width of formation

Width of formation or roadway width is the sum of the widths of pavements or carriage way including separators and shoulders. This does not include the extra land in formation/cutting. The values suggested by IRC are given in Table 1.

Table 1: Width of formation for various classed of roads

Road classification	**Roadway width in m**	
	Plain and rolling terrain	**Mountainous and steep terrain**
NH/SH	**12**	**6.25-8.8**
MDR	**9**	**4.75**
ODR	**7.5-9.0**	**4.75**
VR	**7.5**	**4.0**

7. Right of way

Right of way (ROW) or land width is the width of land acquired for the road, along its alignment. It should be adequate to accommodate all the cross-sectional elements of the highway and may reasonably provide for future development. To prevent ribbon development along highways, control lines and building lines may be provided. Control line is a line which represents the nearest limits of future uncontrolled building activity in relation to a road. Building line represents a line on either side of the road; between which and the road no building activity is permitted at all. The right of way width is governed by:

Width of formation: It depends on the category of the highway and width of roadway and road margins. Height of embankment or depth of cutting: It is governed by the topography and the vertical alignment. Side slopes of embankment or cutting: It depends on the height of the slope, soil type etc. Drainage system and their size which depends on rainfall, topography etc.

Sight distance considerations: On curves etc. there is restriction to the visibility on the inner side of the curve due to the presence of some obstructions like building structures etc.

Reserve land for future widening: Some land has to be acquired in advance anticipating future developments like widening of the road.

Table 1: Normal right of way for open areas

Road	Roadway width in m	
Classification	Plain and	Mountainous and
	rolling terrain	steep terrain
Open areas		
NH/SH	45	24
MDR	25	18
ODR	15	15
VR	12	9
Built-up areas		
NH/SH	30	20
MDR	20	15
ODR	15	12
VR	10	9

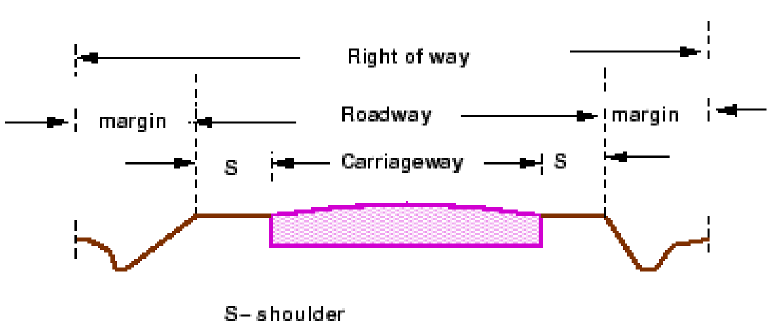


Figure 1: A typical Right of way (ROW)

- The importance of reserved land is emphasized by the following. Extra width of land is available for the construction of roadside facilities. Land acquisition is not possible later, because the land may be occupied for various other purposes (buildings, business etc.) The normal ROW requirements for built up and open areas as specified by IRC is given in Table 1 A typical cross section of a ROW is given in Figure 1.

<u>Sight distance</u>

The safe and efficient operation of vehicles on the road depends very much on the visibility of the road ahead of the driver. Thus the geometric design of the road should be done such that any obstruction on the road length could be visible to the driver from some distance ahead . This distance is said to be the sight distance.

Types of sight distance

Sight distance available from a point is the actual distance along the road surface, over which a driver from a specified height above the carriage way has visibility of stationary or moving objects.

Three sight distance situations are considered for design:

- Stopping sight distance (SSD) or the absolute minimum sight distance
- Intermediate sight distance (ISD) is defined as twice SSD
- Overtaking sight distance (OSD) for safe overtaking operation

Head light sight distance is the distance visible to a driver during night driving under the illumination of head lights. Safe sight distance to enter into an intersection. The most important consideration in all these is that at all times the driver traveling at the design speed of the highway must have sufficient carriageway distance within his line of vision to allow him to stop his vehicle before colliding with a slowly moving or stationary object appearing suddenly in his own traffic lane.

The computation of sight distance depends on:

A. **Reaction time of the driver:**

Reaction time of a driver is the time taken from the instant the object is visible to the driver to the instant when the brakes are applied. The total reaction time may be split up into four components based on PIEV theory. In practice, all these times are usually combined into a total perception-reaction time suitable for design purposes as well as for easy measurement. Many of the studies shows that drivers require about 1.5 to 2 secs under normal conditions. However, taking into consideration the variability of driver characteristics, a higher value is normally used in design. For example, IRC suggests a reaction time of 2.5 secs.

B. **Speed of the vehicle**

The speed of the vehicle very much affects the sight distance. Higher the speed, more time will be required to stop the vehicle. Hence it is evident that, as the speed increases, sight distance also increases.

C. Efficiency of brakes

The efficiency of the brakes depends upon the age of the vehicle, vehicle characteristics etc. If the brake efficiency is 100%, the vehicle will stop the moment the brakes are applied. But practically, it is not possible to achieve 100% brake efficiency. Therefore the sight distance required will be more when the efficiency of brakes are less. Also for safe geometric design, we assume that the vehicles have only 50% brake efficiency.

D. Frictional resistance between the tyre and the road

The frictional resistance between the tyre and road plays an important role to bring the vehicle to stop. When the frictional resistance is more, the vehicles stop immediately. Thus sight required will be less. No separate provision for brake efficiency is provided while computing the sight distance. This is taken into account along with the factor of longitudinal friction. IRC has specified the value of longitudinal friction in between 0.35 to 0.4.

E. Gradient of the road.

Gradient of the road also affects the sight distance. While climbing up a gradient, the vehicle can stop immediately. Therefore sight distance required is less. While descending a gradient, gravity also comes into action and more time will be required to stop the vehicle. Sight distance required will be more in this case.

<u>Stopping sight distance</u>

Stopping sight distance (SSD) is the minimum sight distance available on a highway at any spot having sufficient length to enable the driver to stop a vehicle traveling at design speed, safely without collision with any other obstruction.
There is a term called safe stopping distance and is one of the important measures in traffic engineering. It is the distance a vehicle travels from the point at which a situation is first perceived to the time the deceleration is complete. Drivers must have adequate time if they are to suddenly respond to a situation. Thus in highway design, sight distance at least equal to the safe stopping distance should be provided. The stopping sight distance is the sum of lag distance and the braking distance.

Lag distance is the distance the vehicle traveled during the reaction time t and is given by vt, where v is the velocity in m/sec^2.

Braking distance is the distance traveled by the vehicle during braking operation. For a level road this is obtained by equating the work done in stopping the vehicle and the kinetic energy of the vehicle. If F is the maximum frictional force developed and the braking distance is l, then work done against friction in stopping the vehicle is $Fl=Wfl$ where W is the total weight of the vehicle. The kinetic energy at the design speed is

$$\frac{1}{2}mv^2 = \frac{1}{2}\frac{Wv^2}{g}$$

$$fWl = \frac{Wv^2}{2g}$$

$$l = \frac{v^2}{2gf}$$

Therefore, the SSD = lag distance + braking distance and given by:

$$SSD = vt + \frac{v^2}{2gf} \qquad (1)$$

Where **v** is the design speed in **m/sec²**
t is the reaction time in **sec**
g is the acceleration due to gravity and
f is the coefficient of friction.
The coefficient of friction f is given below for various design speed.

Table 1: **Coefficient of longitudinal friction**

Speed, kmph	< 30	40	50	60	> 80
f	0.40	0.38	0.37	0.36	0.35

When there is an ascending gradient of say **+n %**, the component of gravity adds to braking action and hence braking distance is decreased. The component of gravity acting parallel to the surface which adds to the braking force is equal to **W sin α≈ W tan α = Wn/100**. Equating kinetic energy and work done:

$$\left(fW + \frac{Wn}{100}\right) l = \frac{Wv^2}{2g}$$

$$l = \frac{v^2}{2g\left(f + \frac{n}{100}\right)}$$

Similarly the braking distance can be derived for a descending gradient. Therefore the general equation is given by Equation 2.

$$SSD = vt + \frac{v^2}{2g(f \pm 0.01n)} \tag{2}$$

<u>Overtaking sight distance</u>

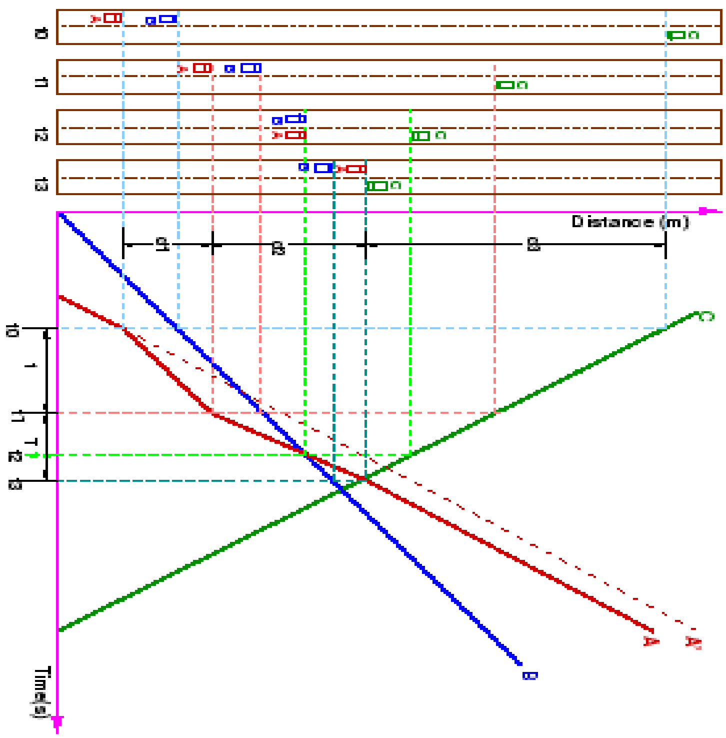


Figure 1: Time-space diagram: Illustration of overtaking sight distance

The overtaking sight distance is the minimum distance open to the vision of the driver of a vehicle intending to overtake the slow vehicle ahead safely against the traffic in the opposite direction. The overtaking sight distance or passing sight distance is measured along the center line of the road over which a driver with his eye level 1.2 m above the road surface can see the top of an object 1.2 m above the road surface.

<u>The factors that affect the OSD are</u>:

- Velocities of the overtaking vehicle, overtaken vehicle and of the vehicle coming in the opposite direction.
- Spacing between vehicles, which in-turn depends on the speed

- Skill and reaction time of the driver
- Rate of acceleration of overtaking vehicle
- Gradient of the road

d_1 the distance traveled by overtaking vehicle A during the reaction time

d_d the distance traveled by the vehicle during the actual overtaking operation

d_3 is the distance traveled by on-coming vehicle C during the overtaking operation

Therefore:

$$OSD = d_1 + d_2 + d_3 \qquad (1)$$

It is assumed that the vehicle **A** is forced to reduce its speed to $\mathbf{v_b}$, the speed of the slow moving vehicle **B** and travels behind it during the reaction time **t** of the driver. So $\mathbf{d_1}$ is given by:

$$d_1 = v_b t \qquad (2)$$

Then the vehicle **A** starts to accelerate, shifts the lane, overtake and shift back to the original lane. The vehicle **A** maintains the spacing **s** before and after overtaking. The spacing **s** in m is given by:

$$s = 0.7v_b + 6 \qquad (3)$$

Let **T** be the duration of actual overtaking. The distance traveled by B during the overtaking operation is $\mathbf{2s+v_bT}$. Also, during this time, vehicle **A** accelerated from initial velocity $\mathbf{v_b}$ and overtaking is completed while reaching final velocity **v**. Hence the distance traveled is given by:

$$\begin{aligned}
d_2 &= v_b T + \frac{1}{2}aT^2 \\
2s + v_b T &= v_b T + \frac{1}{2}aT^2 \\
2s &= \frac{1}{2}aT^2 \\
T &= \sqrt{\frac{4s}{a}} \\
d_2 &= 2s + v_b\sqrt{\frac{4s}{a}} \qquad (4)
\end{aligned}$$

The distance traveled by the vehicle C moving at design speed **v, m/sec** during overtaking operation is given by:

$$d_3 = vT \quad (5)$$

The overtaking sight distance is

$$OSD = v_b t + 2s + v_b\sqrt{\frac{4s}{a}} + vT \quad (6)$$

where $\mathbf{v_b}$ is the velocity of the slow moving vehicle in **m/sec^2**, t the reaction time of the driver in sec, s is the spacing between the two vehicle in m given by **equation 3** and a is the overtaking vehicles acceleration in **m/sec^2**. In case the speed of the overtaken vehicle is not given, it can be assumed that it moves 16 kmph slower the design speed.

The acceleration values of the fast vehicle depends on its speed and given in Table 1.

Table 1: Maximum overtaking acceleration at different speeds

Speed	**Maximum overtaking**
(kmph)	**acceleration (m/sec ^{2})**
25	**1.41**
30	**1.30**
40	**1.24**
50	**1.11**
65	**0.92**
80	**0.72**
100	**0.53**

Note that:

On divided highways, $\mathbf{d_3}$ need not be considered

On divided highways with four or more lanes, IRC suggests that it is not necessary to provide the OSD, but only SSD is sufficient.

Overtaking zones

Overtaking zones are provided when OSD cannot be provided throughout the length of the highway. These are zones dedicated for overtaking operation, marked with wide roads. The desirable length of overtaking zones is 5 times OSD and the minimum is three times OSD (Figure 1).

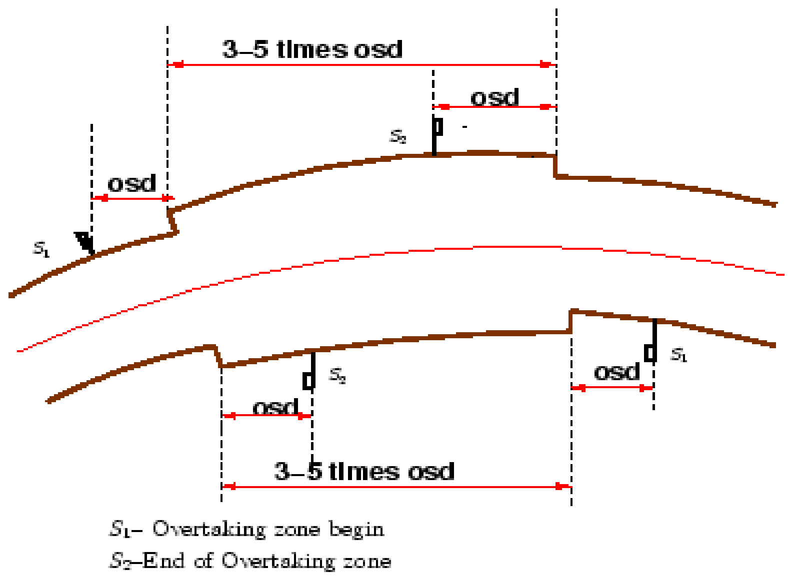


Figure 1: Overtaking zones

Sight distance at intersections

At intersections where two or more roads meet, visibility should be provided for the drivers approaching the intersection from either sides. They should be able to perceive a hazard and stop the vehicle if required. Stopping sight distance for each road can be computed from the design speed. The sight distance should be provided such that the drivers on either side should be able to see each other. This is illustrated in the figure 1.

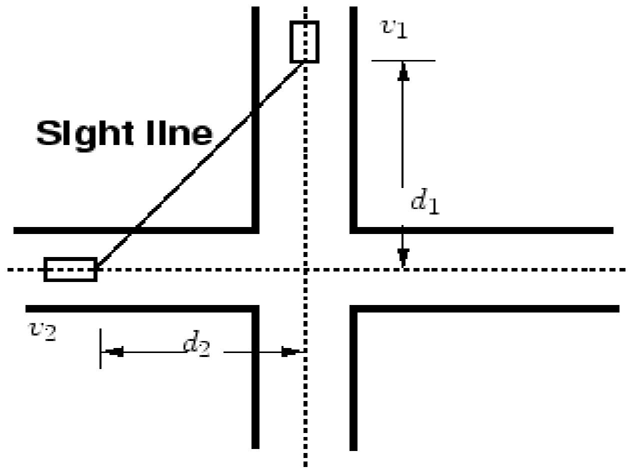


Figure 1: Sight distance at intersections

Design of sight distance at intersections may be used on three possible conditions:

- Enabling approaching vehicle to change the speed
- Enabling approaching vehicle to stop
- Enabling stopped vehicle to cross a main road

<u>Design of Horizontal Alignment:</u>

Horizontal alignment design involves the understanding on the design aspects such as design speed and the effect of horizontal curve on the vehicles. The horizontal curve design elements include design of super elevation, extra widening at horizontal curves, design of transition curve, and set back distance.

<u>Design Speed:</u>

The design speed, as noted earlier, is the single most important factor in the design of horizontal alignment. The design speed also depends on the type of the road. For e.g, the design speed expected from a National highway will be much higher than a village road, and hence the curve geometry will vary significantly.

The design speed also depends on the type of terrain. A plain terrain can afford to have any geometry, but for the same standard in a hilly terrain requires substantial cutting and filling implying exorbitant costs as well as safety concern due to unstable slopes. Therefore, the design speed is normally reduced for terrains with steep slopes.

For instance, Indian Road Congress (IRC) has classified the terrains into four categories, namely plain, rolling, mountainous, and steep based on the cross slope as given in table 1. Based on the type of road and type of terrain the design speed varies. The IRC has suggested desirable or ruling speed as well as minimum suggested design speed and is tabulated in table 2.

Table 1: Terrain classification

Terrain classification	Cross slope (%)
Plain	0-10
Rolling	10-25
Mountainous	25-60
Steep	$>$ 60

The recommended design speed is given in Table 2.

Table 2: Design speed in km/hr as per IRC (ruling and minimum)

Type	Plain	Rolling	Hilly	Steep
NS&SH	100-80	80-65	50-40	40-30
MDR	80-65	65-50	40-30	30-20
ODR	65-50	50-40	30-25	25-20
VR	50-40	40-35	25-20	25-20

Horizontal curve

The presence of horizontal curve imparts centrifugal force which is a reactive force acting outward on a vehicle negotiating it. Centrifugal force depends on speed and radius of the horizontal curve and is counteracted to a certain extent by transverse friction between the tyre and pavement surface. On a curved road, this force tends to cause the vehicle to overrun or to slide outward from the centre of road curvature. For proper design of the curve, an understanding of the forces acting on a vehicle taking a horizontal curve is necessary. Various forces acting on the vehicle are illustrated in the figure 1.

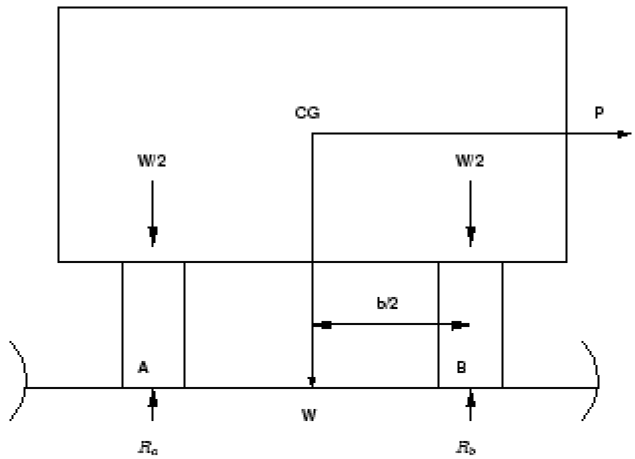


Figure 1: Effect of horizontal curve

They are the centrifugal force (**P**) acting outward, weight of the vehicle (**W**) acting downward, and the reaction of the ground on the wheels (R_A and R_B). The centrifugal force and the weight are assumed to be from the centre of gravity which is at h units above the ground. Let the wheel base be assumed as b units. The centrifugal force **P** in kg/m^2 is given by

$$P = \frac{Wv^2}{gR} \tag{1}$$

where **W** is the weight of the vehicle in **kg**, **v** is the speed of the vehicle in m/sec, **g** is the acceleration due to gravity in m/sec^2 and **R** is the radius of the curve in **m**.

The centrifugal ratio or the impact factor P/W is given by:

$$\frac{P}{W} = \frac{v^2}{gR} \tag{1}$$

The centrifugal force has two effects: A tendency to overturn the vehicle about the outer wheels and a tendency for transverse skidding. Taking moments of the forces with respect to the outer wheel when the vehicle is just about to override,

$$Ph = W\frac{b}{2} \quad \text{or} \quad \frac{\mathrm{P}}{\mathrm{W}} = \frac{\mathrm{b}}{2\mathrm{h}}$$

At the equilibrium over turning is possible when

$$\frac{v^2}{gR} = \frac{b}{2h}$$

and for safety the following condition must satisfy:

$$\frac{b}{2h} > \frac{v^2}{gR} \tag{2}$$

The second tendency of the vehicle is for transverse skidding. i.e. When the the centrifugal force **P** is greater than the maximum possible transverse skid resistance due to friction between the pavement surface and tyre. The transverse skid resistance (F) is given by:

$$\begin{aligned} F = & \quad F_A + F_B \\ = & \; f(R_A + R_B) \\ = & \quad fW \end{aligned}$$

Where F_A and F_B is the fractional force at tire A and B, R_A and R_B is the reaction at tyre A and B, **f** is the lateral coefficient of friction and W is the weight of the vehicle. This is counteracted by the centrifugal force (P), and equating:

$$P = fW \quad \text{or} \quad \frac{\mathrm{P}}{\mathrm{W}} = \mathrm{f}$$

At equilibrium, when skidding takes place (from equation1)

$$\frac{P}{W} = f = \frac{v^2}{gR}$$

and for safety the following condition must satisfy:

$$f > \frac{v^2}{gR} \tag{3}$$

Equation 2 and 3 give the stable condition for design. If equation 2 is violated, the vehicle will overturn at the horizontal curve and if equation 3 is violated, the vehicle will skid at the horizontal curve

Analysis of super-elevation

Super-elevation or cant or banking is the transverse slope provided at horizontal curve to counteract the centrifugal force, by raising the outer edge of the pavement with respect to the inner edge, throughout the length of the horizontal curve. When the outer edge is raised, a component of the curve weight will be complimented in counteracting the effect of centrifugal force. In order to find out how much this raising should be, the following analysis may be done. The forces acting on a vehicle while taking a horizontal curve with superelevation is shown in figure 1.

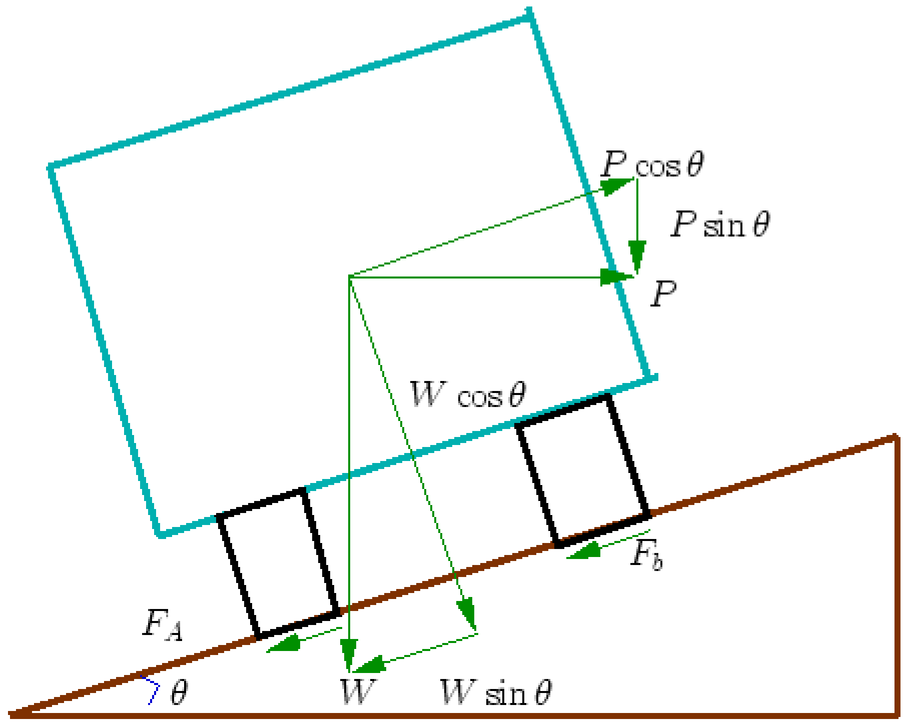


Figure 1: Analysis of super-elevation

Forces acting on a vehicle on horizontal curve of radius R mts at a speed of v, m/sec^2 are:

P the centrifugal force acting horizontally out-wards through the center of gravity,

W the weight of the vehicle acting down-wards through the center of gravity, and F the friction force between the wheels and the pavement, along the surface inward.

At equilibrium, by resolving the forces parallel to the surface of the pavement we get,

$$\begin{aligned} P\cos\theta &= W\sin\theta + F_A + F_B \\ &= W\sin\theta + f(R_A + R_B) \\ &= W\sin\theta + f(W\cos\theta + P\sin\theta) \end{aligned}$$

where W is the weight of the vehicle, P is the centrifugal force, f is the coefficient of friction, θ is the transverse slope due to superelevation. Dividing by W cos θ, we get:

$$\frac{P\cos\theta}{W\cos\theta} = \frac{W\sin\theta}{W\cos\theta} + \frac{fW\cos\theta}{W\cos\theta} + \frac{fPsin\theta}{W\cos\theta}$$

$$\frac{P}{W} = \tan\theta + f + f\frac{P}{W}\tan\theta$$

$$\frac{P}{W}(1 - f\tan\theta) \qquad = \quad \tan\theta + f$$

$$\frac{P}{W} \qquad = \quad \frac{\tan\theta + f}{1 - f\tan\theta} \qquad (1)$$

We have already derived an expression for P/W. By substituting this in equation 1, we get:

$$\frac{v^2}{gR} = \frac{\tan\theta + f}{1 - f\tan\theta} \quad (2)$$

This is an exact expression for superelevation. But normally, f=0.15 and θ<4°, 1-f tan θ≈1 and for small θ, tan θ ≈ sin θ= E/B = e , then equation 2 becomes:

$$e + f = \frac{v^2}{gR} \qquad (3)$$

where, e e is the rate of super elevation, f the coefficient of lateral friction 0.15, v the speed of the vehicle in m/sec^2, R the radius of the curve in m and g=9.8 m/sec^2.

Three specific cases that can arise from equation 3 are as follows:

1. If there is no friction due to some practical reasons, then f=0 and equation 3 becomes$e = \frac{v^2}{gR}$. This result in the situation where the pressure on the outer and inner wheels are same; requiring very high super-elevation e.
2. If there is no super-elevation provided due to some practical reasons, then e= 0 and equation 3 becomes$f = \frac{v^2}{gR}$. . This results in a very high coefficient of friction.
3. If e=0 and f=0.15 then for safe traveling speed from equation 3 is given by $v_b = \sqrt{fgR}$ where v_b is the restricted speed.

<u>Guidelines on superelevation</u>

While designing the various elements of the road like superelevation, we design it for a particular vehicle called design vehicle which has some standard weight and dimensions. But in the actual case, the road has to cater for mixed traffic. Different vehicles with different dimensions and varying speeds ply on the road. For example, in the case of a heavily loaded truck with high centre of gravity and low speed, superelevation should be less; otherwise chances of toppling are more. Taking into practical considerations of all such situations, IRC has given some guidelines about the maximum and minimum superelevation etc.

<u>Design of super-elevation</u>

For fast moving vehicles, providing higher superelevation without considering coefficient of friction is safe, i.e. centrifugal force is fully counteracted by the weight of the vehicle or superelevation. For slow moving vehicles, providing lower superelevation considering coefficient of friction is safe, i.e.centrifugal force is counteracted by superelevation and coefficient of friction. IRC suggests following design procedure:

Step 1

Find e for 75 percent of design speed, neglecting f, i.e $e_1 = \frac{(0.75v)^2}{gR}$.

Step 2

If $e_1 \leq 0.07$, then $e = e_1 = \frac{(0.75v)^2}{gR}$, else if $e_1 > 0.07$ go to step 3.

Step 3

Find f_1 for the design speed and max e, i.e $f_1 = \frac{v^2}{gR} - e = \frac{v^2}{gR} - 0.07$. If $f_1 < 0.15$, then the maximum e=0.07 is safe for the design speed, else go to step 4.

Step 4

Find the allowable speed v_a for the maximum e=0.07 and f=0.15, $v_a = \sqrt{0.22gR}$ If $v_a \geq v$ then the design is adequate, otherwise use speed adopt control measures or look for speed control measures.

Maximum and Minimum Super-Elevation

Depends on
(a) slow moving vehicle and
(b) heavy loaded trucks with high cg. IRC specifies a maximum super-elevation of 7 percent for plain and rolling terrain, while that of hilly terrain is 10 percent and urban road is 4 percent. the minimum super elevation is 2-4 percent for drainage purpose, especially for large radius of the horizontal curve.

Attainment of super-elevation

Elimination of the crown of the cambered section by:

Rotating the outer edge about the crown : The outer half of the cross slope is rotated about the crown at a desired rate such that this surface falls on the same plane as the inner half.

Shifting the position of the crown: This method is also known as diagonal crown method. Here the position of the crown is progressively shifted outwards, thus increasing the width of the inner half of cross section progressively.

Rotation of the pavement cross section to attain full super elevation by:There are two methods of attaining superelevation by rotating the pavement

Rotation about the center line : The pavement is rotated such that the inner edge is depressed and the outer edge is raised both by half the total amount of superelevation, i.e., by $E/2$ with respect to the centre.

Rotation about the inner edge: Here the pavement is rotated raising the outer edge as well as the centre such that the outer edge is raised by the full amount of superelevation with respect to the inner edge.

Radius of Horizontal Curve

The radius of the horizontal curve is an important design aspect of the geometric design. The maximum comfortable speed on a horizontal curve depends on the radius of the curve. Although it is possible to design the curve with maximum superelevation and coefficient of friction, it is not desirable because re-alignment would be required if the design speed is increased in future. Therefore, a ruling minimum radius R_{ruling} can be derived by assuming maximum superelevation and coefficient of friction.

$$R_{\text{ruling}} = \frac{v^2}{g(e+f)} \tag{1}$$

Ideally, the radius of the curve should be higher than R_{ruling}. However, very large curves are also not desirable. Setting out large curves in the field becomes difficult. In addition, it also enhances driving strain.

Extra widening

Extra widening refers to the additional width of carriageway that is required on a curved section of a road over and above that required on a straight alignment. This widening is done due to two reasons: the first and most important is the additional width required for a vehicle taking a horizontal curve and the second is due to the tendency of the drivers to ply away from the edge of the carriageway as they drive on a curve. The first is referred as the mechanical widening and the second is called the psychological widening.

Mechanical widening

The reasons for the mechanical widening are: When a vehicle negotiates a horizontal curve, the rear wheels follow a path of shorter radius than the front wheels as shown in figure 4. This phenomenon is called off-tracking, and has the effect of increasing the effective width of a road space required by the vehicle. Therefore, to provide the same clearance between vehicles traveling in opposite direction on curved roads as is provided on straight sections, there must be extra width of carriageway available. This is an important factor when high proportions of vehicles are using the road. Trailor trucks also need extra carriageway, depending on the type of joint. In addition speeds higher than the design speed causes transverse skidding which requires additional width for safety purpose. The expression for extra width can be derived from the simple geometry of a vehicle at a horizontal curve as shown in figure 4. Let R_1 is the radius of the outer track line of the rear wheel, R_2 is the radius of the outer track line of the front wheel **l** is the distance between the front and rear wheel, n is the number of lanes, then the mechanical widening W_m (refer figure 1) is derived below:

$$\begin{aligned} R_2^2 &= R_1^2 + l^2 \\ &= (R_2 - W_m)^2 + l^2 \\ &= R_2^2 - 2R_2W_m + W_m^2 + l^2 \\ 2R_2W_m - W_m^2 &= l^2 \end{aligned}$$

Therefore the widening needed for a single lane road is:

$$W_m = \frac{l^2}{2R_2 - W_m} \tag{1}$$

If the road has n lanes, the extra widening should be provided on each lane. Therefore, the extra widening of a road with n lanes is given by,

$$W_m = \frac{nl^2}{2R_2 - W_m} \tag{2}$$

Please note that for large radius, $R_2 \approx R$, which is the mean radius of the curve, then W_m is given by:

$$W_m = \frac{nl^2}{2R} \tag{3}$$

Psychological widening

Widening of pavements has to be done for some psychological reasons also. There is a tendency for the drivers to drive close to the edges of the pavement on curves. Some extra space is to be provided for more clearance for the crossing and overtaking operations on curves. IRC proposed an empirical relation for the psychological widening at horizontal curves W_{ps}:

$$W_{ps} = \frac{v}{2.64\sqrt{R}} \tag{4}$$

Therefore, the total widening needed at a horizontal curve W_e is:

$$\begin{aligned} W_e &= W_m + W_{ps} \\ &= \frac{nl^2}{2R} + \frac{v}{2.64\sqrt{R}} \end{aligned} \tag{5}$$

(OR) $$W_e = \frac{nl^2}{2R} + \frac{V}{9.5\sqrt{R}} \quad (\text{kmph})$$

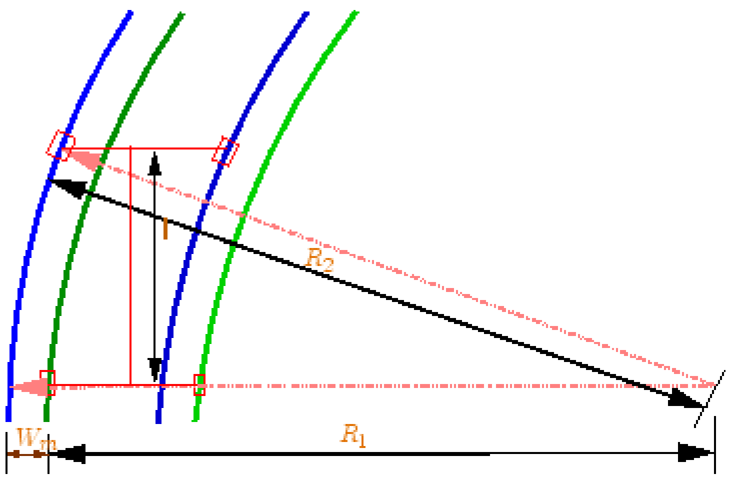


Figure 1: Extra-widening at a horizontal curve

In our country, the design of super-elevation follows IRC guidelines wherein the initial design is done by considering 75% of design speed and the safety of design is assessed. Pavement is to be given extra width at curves to account for mechanical and psychological aspects.

Horizontal Transition Curves

Transition curve is provided to change the horizontal alignment from straight to circular curve gradually and has a radius which decreases from infinity at the straight end (tangent point) to the desired radius of the circular curve at the other end (curve point) There are five objectives for providing transition curve and are given below:

1. to introduce gradually the centrifugal force between the tangent point and the beginning of the circular curve, avoiding sudden jerk on the vehicle.This increases the comfort of passengers.
2. to enable the driver turn the steering gradually for his own comfort and security,
3. to provide gradual introduction of super elevation, and
4. to provide gradual introduction of extra widening.
5. to enhance the aesthetic appearance of the road.

Type of transition curve

Different types of transition curves are spiral or clothoid, cubic parabola, and Lemniscate. IRC recommends spiral as the transition curve because:

It fulfills the requirement of an ideal transition curve, that is;

1. rate of change or centrifugal acceleration is consistent (smooth) and
2. radius of the transition curve is ∞ at the straight edge and changes to R at the curve point ($L_s \alpha 1/R$) and calculation and field implementation is very easy.

Length of transition curve

The length of the transition curve should be determined as the maximum of the following three criteria: rate of change of centrifugal acceleration, rate of change of superelevation, and an empirical formula given by IRC.

1. Rate of change of centrifugal acceleration

At the tangent point, radius is infinity and hence centrifugal acceleration is zero. At the end of the transition, the radius R has minimum value R. The rate of change of centrifugal acceleration should be adopted such that the design should not cause discomfort to the drivers. If c is the rate of change of centrifugal acceleration, it can be written as:

$$c = \frac{\frac{v^2}{R} - 0}{t},$$

$$= \frac{\frac{v^2}{R}}{\frac{L_s}{v}},$$

$$= \frac{v^3}{L_s R}.$$

Therefore, the length of the transition curve L_{s1} in m is

$$L_{s_1} = \frac{v^3}{cR},$$

$$C = \frac{80}{(75+V)} \text{ m/sec}^3, [0.5 < C < 0.8] \qquad (1)$$

i.e., the minimum and maximum values of C are limited to 0.5 and 0.8 respectively.

If the design speed is V kmph;

$$L_s = \frac{v^3}{(3.6)^3 CR}$$

i.e.,

$$L_s = \frac{V^3}{46.5CR} = \frac{0.0215\,V^3}{CR} \qquad (4.23)$$

Here,

L_s = length of transition curve, m

C = allowable rate of change of centrifugal acceleration, m/sec^3 as given in Eq. 4.21.

R = radius of the circular curve, m.

2. Rate of introduction of super-elevation

Raise (E) of the outer edge with respect to inner edge is given by $E=eB=e(W+W_e)$. The rate of change of this raise from 0 to E is achieved gradually with a gradient of 1 in N over the length of the transition curve (typical range of N is 60-150). Therefore, the length of the transition curve L_{s2} is:

$$L_{s_2} = Ne(W + W_e) \qquad (3)$$

3. By empirical formula

IRC suggest the length of the transition curve is minimum for a plain and rolling terrain:

(a) For plain and rolling terrain :

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

(b) For mountainous and steep terrains;

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

and the shift s as:

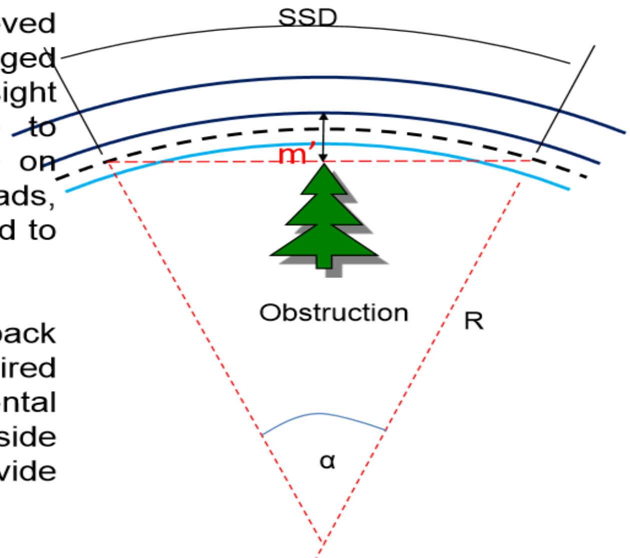
$$s = \frac{L_s^2}{24R} \qquad (6)$$

The length of the transition curve L_s is the maximum of equations 1, 3 and 4or5, i.e.

$$L_s = \text{Max}: \ (L_{s_1}, L_{s_2}, L_{s_3})$$

Set-back distance on horizontal curve

Where there are sight obstruction like buildings, cut slope or trees on the inner sides of the curves, either the obstruction should be removed or the alignment should be changed in order to provide adequate sight distance. If it is not possible to provide adequate sight distance on the curves on existing roads, regulatory sign should be installed to control the traffic suitably.



clearance distance or set-back distance is the distance required from the centre line of a horizontal curve to an obstruct on the inner side of the of the curve to provide adequate sight distance

Case-I: if length of curve (Lc) > sight distance(S)

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

$$\frac{\alpha'}{2} = \frac{180S}{2\pi(R - d)}$$

Where,
M' = set-back distance
d = the distance between the centre line of the road and the centre line of the inside lane in 'm'
R = radius of the curve in 'm'
α = angle subtended by the arc length 'S' at the centre

Case-II: if length of curve (Lc) < sight distance(S)

$$\boxed{m' = R - (R-d)\cos\frac{\alpha'}{2} + \frac{S - L_C}{2}\,Sin\,\frac{\alpha'}{2}}$$

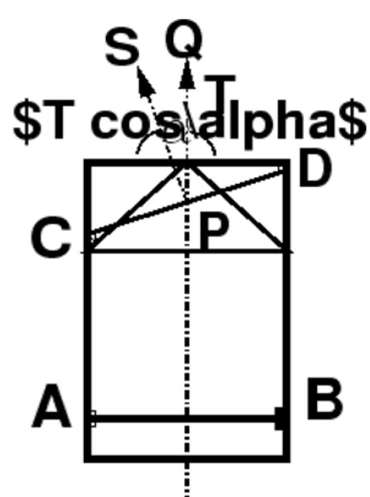
$$\boxed{\frac{\alpha'}{2} = \frac{180 L_C}{2\pi(R-d)}}$$

Where ‘Lc’ is the length of curve and ‘S’ is the sight distance

Curve resistance

The automobiles are steered by turning the front wheels, but the rear wheels do not turn. When a vehicle driven by rear wheels move on a horizontal curve, the direction of rotation of rear and front wheels are different and so there is some losses in the tractive froce.

thus the loss of tractive force due to turning of a vehicle on a horizontal curve , which is termed as curve resistance will be equal to (T- T cos α) or T (1-cos α) and will depend on turning angle α



Vertical alignment

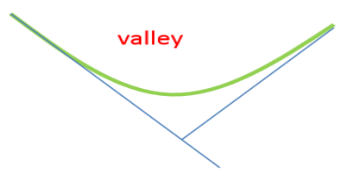
The vertical alignment is the elevation or profile of the centre line of the road.
The vertical alignment consist of grade and vertical curve and it influence the vehicle speed, acceleration, sight distance and comfort in vehicle movements at high speed.

Gradient

- It is the rate of rise or fall along the length of the road with respect to the horizontal. It is expressed as a ratio of 1 in x (1 vertical unit to x horizontal unit). Some times the gradient is also expressed as a percentage i.e. n% (n in 100).
- Represented by:

+n %   + 1 in X (+ve or Ascending)

or -n%   - 1 in X (-ve or descending)



Typical Gradients (IRC)

- Ruling Gradient
- Limiting Gradient
- Exceptional gradient
- Minimum Gradient
- Ruling gradient (design gradient):
- It is the maximum gradient within which the designer attempts to design the vertical profile of road, it depends on
  - Type of terrain
  - Length of grade
  - Speed
  - Pulling power of vehicles
  - Presence of horizontal curves
  - Mixed traffic

Limiting Gradient:

- Steeper than ruling gradient. In hilly roads, it may be frequently necessary to exceed ruling gradient and adopt limiting gradient, it depends on
  - Topography
  - Cost in constructing the road

Exceptional Gradient:

- Exceptional gradient are very steeper gradients given at unavoidable situations. They should be limited for short stretches not exceeding about 100 m at a stretch.

critical length of the grade:

- The maximum length of the ascending gradient which a loaded truck can operate without undue reduction in speed is called critical length of the grade. A speed of 25 kmph is a reasonable value. This value depends on the size, power, load, initial speed.

Minimum gradient

- This is important only at locations where surface drainage is important. Camber will take care of the lateral drainage. But the longitudinal drainage along the side drains require some slope for smooth flow of water. Therefore minimum gradient is provided for drainage purpose and it depends on the rain fall, type of soil and other site conditions.
- A minimum of 1 in 500 may be sufficient for concrete drain and 1 in 200 for open soil drains.

Value of gradient as per IRC

Terrain	Ruling gradient	Limiting gradient	Exceptional gradient
Plain and Rolling	3.3% (1 in 30)	5%	6.70%
Mountainous terrain	5% (1 in 20)	6%	7%
Steep terrain up to 3000m (MSL)	5% (1 in 20)	6%	7%
Steep terrain (>3000m)	6% (1 in 16.7)	7%	8%

SUMMIT CURVE

Length of summit curve(L) for SSD

- Case-1(L > SSD)

$$\boxed{L = \frac{NS^2}{\left(\sqrt{2H} + \sqrt{2h}\right)^2}} \quad \text{or} \quad \boxed{L = \frac{NS^2}{4.4}}$$

- Case-2(L < SSD)

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

length of summit curve for OSD

- Case-1(L > OSD)

$$\boxed{L = \frac{NS^2}{8H}} \quad \text{or} \quad \boxed{L = \frac{NS^2}{9.6}}$$

- Case-2(L < OSD)

$$\boxed{L = 2S - \frac{8H}{N}} \quad \text{or} \quad \boxed{L = 2S - \frac{9.6}{N}}$$

S=sight distance i.e. SSD, OSD or ISD
N= deviation angle
i.e. algebraic difference between two grade
H=height of driver eye above the carriageway i.e. 1.2 m
h=height of driver eye above the carriageway i.e. 0.15 m

VALLEY CURVE

Length of valley curve for comfort condition:

$$\boxed{L = 2\left[\frac{N\left(\frac{V}{3.6}\right)^3}{C}\right]^{\frac{1}{2}}}$$

OR

$$\boxed{L = 0.38\left(NV^3\right)^{\frac{1}{2}}}$$

N= deviation angle i.e. algebraic difference between two grade
C= rate of change of centrifugal acceleration may be taken as 0.6 m/sec³
V= speed of vehicle in kmph

Length of valley curve for head light sight distance

- Case-1(L > SSD)

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

OR

$$\boxed{L = \frac{NS^2}{(1.5 + 0.035S)}}$$

- Case-2(L < SSD)

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

OR

$$\boxed{L = 2S - \frac{(1.5 + 0.035S)}{N}}$$

h1=height of head light above the carriesway
α= inclination of focused portion of the beam of light w.r.t horizontal or beam angle .
N= deviation angle i.e. algebraic difference between two grade.
S=head light distance is equal to SSD

Grade compensation

- At the horizontal curve ,due to the turning angle α of the vehicle, the curve resistance develop is equal to T(1-Cos α). When there is a horizontal curve in addition to the gradient, there will be a increase in resistance to fraction due to both gradient and curve. It is necessary that in such cases the total resistance due to grade and the curve should not exceeded the resistance due to maximum value of the gradient specified.
- Maximum value generally taken as ruling gradient

- Thus grade compensation can be defined as the reduction in gradient at the horizontal curve because of the additional tractive force required due to curve resistance (T−Tcosα), which is intended to offset the extra tractive force involved at the curve.
- IRC gave the following specification for the grade compensation.
    1. Grade compensation is not required for grades flatter than 4% because the loss of tractive force is negligible.
    2. Grade compensation is (30+R)/R %, where 'R' is the radius of the horizontal curve in meters.
    3. The maximum grade compensation is limited to 75/R%.