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# Geometric Design of Highway

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**Abstract**

The paper deals with the objective and factors to be considered for geometric design of highway followed by the features (cross section elements of highway, sight distance considerations, horizontal alignment and vertical alignment) on which the geometric design of highways is based. The paper mainly emphasizes on the importance of planning and designing of geometric features of the highway during the initial alignment itself taking into consideration the future growth of traffic flow and possibility of the road being upgraded to a higher category or to a higher design speed standard at a later stage as it is very expensive and rather difficult to improve the geometric elements of a highway in stages at a later date.

***Keywords:*** *Design Speed, Topography and Cross Section Elements.*

## 1. Introduction

The geometric design of highways deals with the dimensions and layout of visible features of the highway. The emphasis of the geometric design is to address the requirement of the driver and the vehicle such as safety, comfort, efficiency, etc. The features normally considered are the *cross section elements, sight distance considerations, horizontal alignment, vertical alignment* and *intersection*. Proper geometric design will help in the reduction of accidents and their severity. Therefore, the objective of geometric design is to provide optimum efficiency in traffic operation with maximum safety at reasonable cost and minimum environmental impacts. The highway should be considered as an integral part of the environment. It is possible to design and construct the pavement of a road in stages; but it is very expensive and difficult to improve the geometric elements of a road in stages at a later date. Therefore, it is important to plan and design the geometric features of the road during the initial alignment itself taking into consideration the future growth of traffic flow and possibility of the road being upgraded to a higher category or to a higher design speed standard at a later stage. A number of factors are there which affect the geometric design of highways. The important of these factors which control the geometric elements are:

## 2. Design Speed

Design speed is the single most important factor that affects the geometric design. It directly affects the sight distance, horizontal curve, and the length of vertical curves. Since the speed of vehicles vary with driver, terrain etc, a design speed is adopted for all the geometric design. Design speed is defined as the highest continuous speed at which individual vehicles can travel with safety on the highway when weather conditions are conducive. Design speed is different from the legal speed limit which is the speed limit imposed to curb a common tendency of drivers to travel beyond an accepted safe speed. Design speed is also different from the desired speed which is the maximum speed at which a driver would travel when unconstrained by either traffic or local geometry. Since there are wide variations in the speed adopted by different drivers, and by different types of vehicles, design speed should be selected such that it satisfies nearly all drivers. At the same time, a higher design speed has cascading effect in other geometric design and thereby cost escalation. Therefore, an 85th percentile design speed is normally adopted. This speed is defined as that speed which is greater than the speed of 85% of the drivers. In some countries this is as high as 95 to 98 percentile speed.

## 3. Topography

The next important factor that affects the geometric design is the topography. It is easier to construct roads with required standards for a plain terrain. However, for a given design speed, the construction cost increases multiform with the gradient and the terrain. Therefore, geometric design standards are different for different terrain to keep the cost of construction and time of construction under control.

For example the design speed of NH and SH on plane terrain with general cross slope upto 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. As every geometric design element is affected by design speed and design speed is dependent upon topography/terrain, therefore, it may be concluded that topography also affects the geometric design of roads. Further, this is characterized by sharper curves and steeper gradients in hilly terrain due to the construction problems.

## 4. Other Factors

In addition to the design speed and topography, there are various other factors that affect the geometric design and they are briefly discussed below:

- **Vehicle:** The dimensions, weight of the axle and operating characteristics of a vehicle influence the design aspects such as width of the pavement, radii of the curve, clearances, parking geometrics etc. A design vehicle which has standard weight, dimensions and operating characteristics are used to establish highway design controls to accommodate vehicles of a designated type.

- **Human:** The important human factors that influence geometric design are the physical, mental and psychological characteristics of the driver and pedestrians like the *reaction time*.

- **Traffic:** It will be uneconomical to design the road for peak traffic flow. Therefore a reasonable value of traffic volume is selected as the *design hourly volume* which is determined from the various traffic data collected. The geometric design is thus based on this design volume, capacity etc.

- **Environmental Factors:** Factors like air pollution, noise pollution etc. should be given due consideration in the geometric design of roads.

- **Economy:** The design adopted should be economical as far as possible. It should match with the funds allotted for capital cost and maintenance cost.

- **Others:** Geometric design should be such that the aesthetics of the region is not affected.

## 5. Cross Section Elements

**Friction:** Operating speed and sight distance requirement are decided by considering the friction between vehicle tyres and the pavement. The coefficient of friction or the skid resistance offered by the pavement surface under various conditions is important with reference to the safety. The maximum coefficient of friction comes into play only when the braking efficiency is high enough to partially arrest the rotation of wheels on application of brakes, at low speeds.

**Skid:** It occurs when the path travelled along the road surface is more than the circumferential movements of the wheels due to their rotation. Lateral skidding may take place while a vehicle negotiates a horizontal curve when the centrifugal force is greater than the counteracting forces i.e. lateral friction and component of gravity due to super elevation. The lateral skidding is considered dangerous as the vehicle goes out of control leading to an accident. Slip occurs when a wheel revolves more than the corresponding longitudinal movement along the road which usually occurs when a vehicle rapidly accelerates from stationary position on slippery pavement.
For the calculation of stopping distance, the longitudinal frictional values of 0.35 to 0.40 have been recommended by the Indian Road Congress, depending upon the speed whereas, in case of the horizontal curve design, a value of 0.15 has been recommended for the lateral coefficient of friction. This low value has been suggested considering the worst possible surface conditions as it is essential to prevent possible lateral skid even under adverse pavement conditions.

**Camber:** Cross slope or camber is the slope provided to the road surface in the transverse direction to drain off the rain water from the road surface which is considered very important to prevent the entry of surface water into subgrade soil through pavement so that life of the pavement as well as it's skid resistance is not reduced.

The rate of camber depends upon:

- Values of the type of pavement surface, and
- The amount of rainfall.

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**Table1: Recommended Camber for Different Types of Road Surfaces**

| Sl. No. | Types of pavement surface | Range of camber depending upon rainfall Heavy to Light |
|---|---|---|
| 1. | Cement concrete and high type bituminous surface | 1 in 50 (2.0 %) to 1 in 60 (1.7 %) |
| 2. | Thin bituminous surface | 1 in 40 (2.5 %) to 1 in 50 (2.0 %) |
| 3. | Water bound macadam and gravel pavement | 1 in 33 (3.0 %) to 1 in 40 (2.5 %) |
| 4. | Earth | 1 in 25 (4.0 %) to 1 in 33 (3.0 %) |

Camber for shoulders should be 0.5% steeper than that of the adjoining pavement, subject to a minimum of 3.0% (and a maximum value of 5.0% for earth shoulders).

**Carriageway:** Width of pavement or carriageway depends upon the width of traffic lane and number of lanes. The lane width is determined on the basis of width of vehicle and minimum side clearance required from safety point of view. The maximum width of vehicle as per IRC specifications is 2.44 m. Keeping all these in view, a width of 3.75 m is considered desirable for a road having single lane. For pavements having two or more lanes, width of 3.5 m per lane is considered sufficient.

**Kerbs:** Kerb indicates the boundary between pavement and shoulder. Kerbs may be mainly divided in three groups based on their functions:

- *Low or mountable type kerbs* (10 cm above the pavement edge) which though encourage traffic to remain in the through traffic lanes yet allow the driver to enter the shoulder area with little difficulty.

- *Semi-barrier type kerb* (15 cm above the pavement edge) is provided where the pedestrian traffic is high. At acute emergency, it is possible to drive over this kerb with some difficulty.

- *Barrier type kerbs* (20 cm above the pavement edge) is provided in built-up areas adjacent to foot paths with considerable pedestrian traffic.

➢ Width of roadway or formation is the sum of widths of pavements or carriageway including separators if any; and the shoulders.

➢ Right of way is the area of land acquired for the road, along its alignment. The width of this acquired land is known as land width and it depends upon the importance of the road and possible future development.

➢ Building line is the boundary beyond which construction of building is not permitted whereas, building can be constructed between building line and control line but type of the building is controlled.

**Sight Distances:** Sight distance is the length of the road visible ahead to the driver at any instance. Sight distance available at a point is the actual distance along the road surface, which a driver from the specified height above the carriageway has visibility of stationary or moving objects.

**Stopping Sight Distance:** SSD is the minimum sight distance available on a highway at any spot to stop a vehicle travelling at design speed safely without collision with any other obstruction.

**SSD = Lag distance + Braking distance**

*Lag distance* is the distance travelled by the vehicle during total reaction time. If vehicle is assumed to be moving at design speed ‘v’ m/sec and ‘t’ is the reaction time in seconds then Lag distance = v x t meters.

*Reaction time* of a driver is the time taken from the instant the object is visible to the driver to the instant the brakes are effectively applied which depends upon several factors and a value of 2.5 seconds is considered reasonable for most of the situations as recommended by IRC.

*Braking distance* is the distance travelled after application of brakes which mainly depends upon coefficient of friction and speed of the vehicle = $v^2/2gf$; where 'f' is coefficient of friction and 'g' is acceleration due to gravity.

From above discussion,

**SSD = $(vt + v^2/2gf)$**

*On single lane roads when two way movement of traffic is permitted, minimum stopping sight distance should be equal to twice the stopping distance to enable both vehicles coming from opposite directions to stop.*

**Overtaking Sight Distance:** OSD is the minimum sight distance required to overtake a slow moving vehicle ahead with safety against the traffic of the opposite direction.

OSD consists of three parts:

- $d_1$, the distance travelled by overtaking vehicle during the reaction time 't'
- $d_2$, the distance covered by the vehicle during the actual overtaking operation.
- $d_3$, the distance travelled by on-coming vehicle during the overtaking operation time 'T'.

Therefore,

**$OSD = d_1 + d_2 + d_3$**

It is assumed that the overtaking vehicle is forced to reduce its speed to $v_b$, the speed of the slow moving vehicle and travels behind it maintaining space 's' during the reaction time 't' of the driver i.e. till there is an opportunity for safe overtaking operation. Therefore, $d_1 = v_b \times t$

Then the overtaking vehicle starts to accelerate, shifts the lane, overtakes and shifts back to the original lane. The overtaking vehicle maintains the spacing 's' before and after overtaking which is given by; $s = (0.7v_b+6)$ m

Let 'T' be the time taken for overtaking operation; then $d_2 = 2s + v_bT$; $T = \sqrt{(4s/a)}$

Where 'a' is the acceleration of the overtaking vehicle in m/sec$^2$.

Distance travelled by the vehicle coming from opposite direction at design speed 'v' m/sec during the overtaking operation is given by, $d_3 = v \times T$.

From the above discussion,

**$OSD = [v_bt + \{2s + v_b\sqrt{(4s/a)}\} + vT]$**

In case the speed of the overtaken vehicle is not given, it can be assumed that it moves 16 kmph slower than the design speed.

In case, when the required OSD cannot be provided, *Intermediate sight distance (ISD)* equal to twice SSD may be provided.

**Horizontal Alignment:** Alignment design is very important because a bad alignment will enhance the construction, maintenance and vehicle operating cost. Once an alignment is fixed and constructed, it is not easy to change it due to increase in the cost of adjoining land and construction of costly structures by the roadside.

**Horizontal Curves:** Horizontal curves are provided to change the direction of central line of the road. When a vehicle negotiates a horizontal curve, centrifugal force acts outwards through centre of gravity of the vehicle which depends upon the radius of curve and speed of vehicle and is given by the following equation:

**$P = Wv^2/gR$**

Here, P and W are centrifugal force and wt. of vehicle in kg respectively

v is speed of vehicle in m/s and R is radius of the circular curve in meter.

Ratio of centrifugal force to weight of the vehicle is known as centrifugal ratio or impact factor i.e. $P/W = v^2/gR$

Centrifugal force acting on a vehicle negotiating a horizontal curve has two effects:

**Overturning Effect:** To prevent overturning of vehicles, horizontal curves should be designed in such a way that the value of impact factor i.e. $v^2/gR$ never attains a value equal to b/2h where 'b' is the width of wheel base and 'h' is height of c.g. of vehicle above the road surface.

**Transverse Skidding Effect:** To avoid the danger of lateral skidding, horizontal curves should be designed in such a way that value of the impact factor i.e. $v^2/gR$ is always less than the value of coefficient of lateral friction i.e. f.

## 6. Super Elevation

Super elevation should be provided throughout the length of horizontal curve by raising outer edge of the pavement with respect to inner edge to reduce the tendency of any vehicle to overturn or skid while negotiating the horizontal curve. The Super elevation 'e' is expressed as the ratio of the height of outer edge with respect to the horizontal width and it may be written as:

$\mathbf{e = \tan\theta}$

Value of super elevation depends on the radius of curve R (m), speed of vehicle v (m/s) and coefficient of lateral friction f as ($e + f = v^2/gR$). In order to assess the value of super elevation, the speed of vehicle is taken as equal to the design speed of road and minimum value of 'f' for design purpose is standardised equal to 0.15.

- **Maximum Super Elevation:** In case of slow moving heavily loaded vehicles in which centre of gravity are relatively high, it becomes necessary to limit the maximum allowable value of super elevation to prevent the danger of toppling. As per IRC, the value is restricted to 7.0% for plain and rolling terrain, 10% for hill roads and 4.0% for urban road stretches with frequent intersections.

- **Minimum Super Elevation:** If value of the super elevation worked out from the formula comes equal to or less than the camber of road surface then the minimum super elevation to be provided on horizontal curve may be limited to the camber of the surface taking drainage considerations in view i.e. to drain off the surface water.

## 7. Radius of Horizontal Curve

The centrifugal force which is counteracted by super elevation and lateral friction is given by the following relation:

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

Therefore, the radius of a horizontal curve which is required to be provided for safe negotiation of a vehicle travelling at design speed v kmph may be calculated as:

$$R = v^2/g\,(e+f)$$

## 8. Pavement Widening on Horizontal Curves

- **Mechanical Widening:** When a vehicle negotiates a horizontal curve, rear wheels of the vehicle do not follow the same path as followed by front wheels. This phenomenon is called *off tracking*. If inner front wheel travels along the pavement edge at a horizontal curve, inner rear wheel will be off the pavement. To prevent off tracking, extra widening of pavement is provided at horizontal curves which is called mechanical widening;

$W_m = nl^2/2R$

'R' is mean radius of curve, 'n' is no. of lanes and 'l' is length of wheel base.

- **Psychological Widening:** Extra width of the pavement is also provided for psychological reasons such as, to allow for the extra space requirements for the overhangs of vehicles and to provide greater clearance for crossing and overtaking vehicles on the curves. This kind of widening is therefore important for pavements with more than one lane and its value is given by following empirical formula:

$W_{ps} = v/(2.64\sqrt{R})$; v = design speed in m/s

From the above discussion, extra widening of the pavement is given as:

$W_e = \{nl^2/2R\} + \{v/(2.64\sqrt{R})\}$

## 9. Horizontal Transition Curve

To enable gradual introduction of super elevation and the centrifugal force on a vehicle negotiating a horizontal curve avoiding sudden jerk on the vehicle; a transition curve is introduced whose radius reduces from infinity at tangent point to a designed radius of the circular curve.

Ideal shape of the transition curve should be such that the rate of introduction of centrifugal force or rate of change of centrifugal acceleration should be consistent i.e. the radius of the transition curve should consistently decrease from infinity to R and length of transition curve should be inversely proportional to R. The *spiral* transition curve fulfils this requirement of an ideal transition curve.

## 10. Vertical Alignment

The vertical alignment is the elevation or profile of the centre line of the road.

### Vertical Curves:

**Summit Curves or Crest Curves with Convexity upwards:** When a fast moving vehicle travels along summit curve, the centrifugal force will act upwards against gravity and hence a part of the pressure on tyres and spring is relieved. Therefore, there is no problem of discomfort to passengers on summit curves. The only problem is to provide adequate sight distance. Circular summit curve is ideal as sight distance available throughout the length of circular curve is constant. A simple parabola is nearly congruent with a circular arc; also a parabola is very easy for arithmetic manipulation for computing ordinates. Also simple parabolic summit curve gives good riding comfort. Therefore, in actual practice a simple parabola is used as summit curve.

**Valley or Sag Curves with Concavity upwards:** There is no problem of restriction to sight distance during day light. But at night, sight distance is reduced under head light. Also, centrifugal force acts downward adding pressure on springs. Hence the allowable rate of change of centrifugal acceleration should govern the design of valley curves. Therefore, the best shape of valley curve is a transition curve for gradually introducing the centrifugal acceleration. Cubic parabola is generally preferred for valley curves.

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