Chapter 1

Transportation Engineering

CHAPTER HIGHLIGHTS

- *Highway development and planning*
- *Highway alignment and engineering surveys*
- *Highway geometric design*
- *Geometric design of railway track*
- *Airport planning and design*

Highway Development and Planning

Introduction

Transportation is vital for the economic development of any region as it is used to transport people, products, etc. The main objective of good transportation system is to provide safe, economical and efficient system. This chapter explains the development of roads from romans to the present including the developments during all kingdoms and British rule. The present scenario and all road development plans and their objectives are discussed.

In Latin, transportae = to cross across.

Modes of Transport

Highways—Most flexible system (house to house connection)

Railway—Energy consumption less than highways

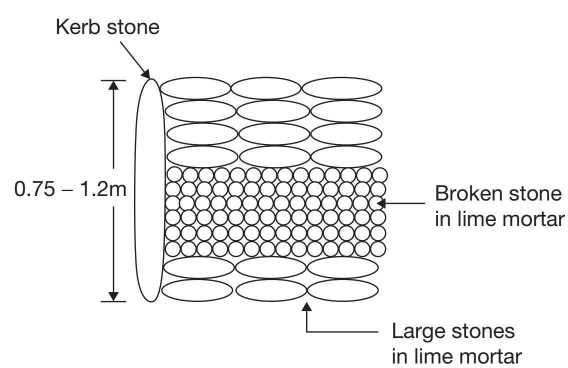
$$\left(\frac{1}{4}-\frac{1}{8}\text{of highways}\right)$$

Waterways—Economical but slow

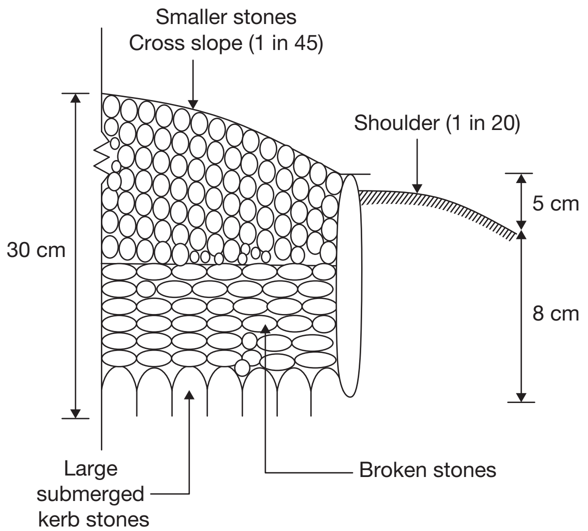
Airways—Costliest of all

Historic Development

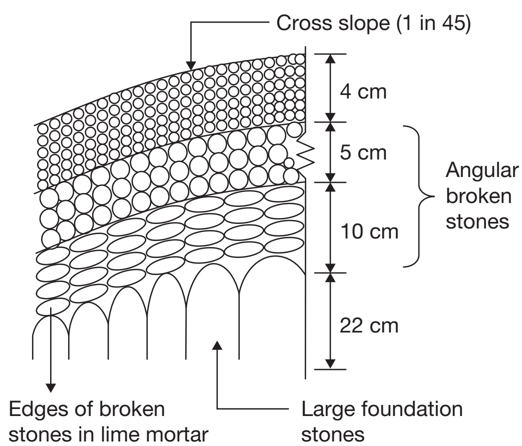
1. **Mesopotamia—3500 BC:** Invention of wheel and necessity of hard surface for wheeled vehicles to move, paved the way for road building.
2. **Roman roads—312 BC:**
   - Pioneers in road construction
   - 580 km (approximately)
   - No cross-slope or gradient



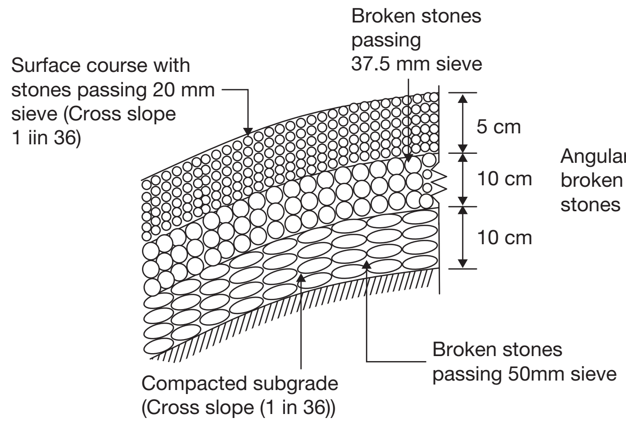
3. **Pierre tresaguet (1716–1796) in France:**
   - Father of modern highway engineering
   - Thickness of road can be only 30 cm
   - Cross-slope of 1 in 45 on top wearing course for surface drainage.
   - Shoulders also with cross-slope to drain surface water to side drain.



4. **Metcalf method (1717–1810) in England—similar to tresaguet:**
   - Followed recommendations of Robert Phillips.
   - 290 km of road in northern region of England.
   - His work was not recorded as he was blind.
5. **Thomas Telford (1757–1834):**
   - Founder of Institution of Civil Engineers at London.
   - Provided cross–slope from foundation itself by varying thickness of foundation stones.
   - Provided cross-drains at intervals of about 90 m.
   - No kerb stones are used.



6. **John McAdams' (1756–1836):**
   - Gave scientific method of road construction.
   - Realised not to provide strong foundation at sub-grade as wheel load of traffic gets dispersed and intensity decreases at lower layers.
   - Sub-grade is compacted and cross-slope of 1 in 36 is provided from sub-grade itself.
   - Improvement of strength of top layers.



Water bound McAdams' – used soil to bind stones.
Bituminous McAdams' – used bitumen as binder.

Highway Development in India

- Excavations of **Mohenjodaro and Harappa** have revealed the existence of roads in India during **23–35 century BC**.
- **Mauryan kings** and **Gupta rulers** also built very good roads.
- Mughal period—Roads were built from North–West to the Eastern areas through Gangetic plains, linking coastal and central parts.

British Rule—19th Century

- Early British maintained only roads of military and administrative importance.
- Prior to introduction of railways, a number of trunk roads were metalled and bridges were constructed.
- Governor General Lord Dalhousie formed the **Public Works Department** in **1865. Grand Trunk Road** was undertaken by this new department.

Development During 20th Century

- During I World War increases in number of vehicles demanded better roads. So, lot of development took place.

1927—Jayakar Committee Formed to examine and submit a report on road development.

Recommendations:

1. Road development to be considered as national interest.
2. Levy tax on petrol and diesel from road users to develop fund called 'Central Road Fund.'
3. Establishing research organisation to carry out research and development of roads and semi-official body to be formed to act as an advisory body on various aspects of roads.

1929 (1st March)—Central Road Fund

- Present tax on petrol and diesel is ₹ 2/litre.

- 20% of annual revenue to be retained as Central reserve and grants are to be given by the Central Government for research on road and bridge projects.
- 80% of annual revenue is distributed to states (based on tax collected for petrol) for road development.

1934—Indian Roads Congress **(Semi-official Technical Body)**
- It is an offshoot of Jayakar committee.
- Controls specifications, standards and guidelines on materials, design and construction of roads and bridges and publishes journals and research publication on Highway Engineering.
- Works with Ministry of Road Transport and Highways.

1939—Motor Vehicle Act **(Revised in 1988 and came into force in 1989)**
- If any vehicle has to occupy the road, tax has to be paid and instructions for road users were given.
- This act is to regulate the road traffic in the form of traffic laws, ordinances and regulations. The three phases primarily covered are:
  (a) Control of the driver
  (b) Vehicle ownership
  (c) Vehicle operation on roads and in traffic stream

1943–63—Nagpur Road Plan **(I 20 year Road Development Plan)**
- Target—16 km road/100 sq.km area of country.
- Achieved target 2 years ahead in 1961.
- This plan assumed '**Star and Grid Pattern**'.
- Divided roads into five categories
  (a) National Highways (NH)
  (b) State Highways (SH)
  (c) Major District Roads (MDR)
  (d) Other District Roads (ODR)
  (e) Village Roads (VR)
- Proposed a formula for calculating the road length of different categories of roads, considering geographical, agricultural and population conditions.

1950—Central Road Research Institute (CPRI) It was started at New Delhi. It is engaged in carrying out applied research in various aspects of highway engineering.

1956—National Highway Act Development and maintenance to be under Central Government.

1988—National Highway Authority of India (NHAI) **(Revised form of National Highway Act)**
- Started opening in 1995.

1961–1981—Bombay Road Plan **(II road development plan)**
Target:
1. 32 km road /100 sq. km area of country (double of Nagpur plan).
2. Expressways of 1600 km length.

1973—Highway Research Board (HRB) Coordination and promotion of highway researches.

1981–2001—Lucknow Road Plan **(III road development plan)**
- Target 82 km/100 sq. km area and expressways 2000 km.
- In 1991, changes were made to include private sector in road development.

Roads are classified into three classes:

1. Primary system
   - Expressways
   - National Highways
2. Secondary system
   - State Highways
   - Major district roads
3. Tertiary system
   - Other district road
   - Village roads

2000—National Highway Development Projects (NHDP) **(Taken up by NHAI)**
Planned road development in different phases to construct roads with uninterrupted flow of traffic.

Phase I—Golden Quadrilateral **(5846 km)**
Mumbai–Chennai–Kolkata–Delhi (All major metropolitan cities)

Phase II:
1. North–South corridor (Srinagar to Kanyakumari)
2. East–West corridor (Silchar to Porbandar) Phase II has total length of 7300 km.

2000—Pradhan Mantri Gram Sadak Yojana (PMGSY) To provide connectivity to all unconnected habitations with population 500 and above with all-weather roads.

Road Development Plan

Vision 2021
- The fourth road development plan has not yet been approved. Instead Road Development plan vision: 2021 has been formulated for the period 2001–2021.
- This vision document has considered the need for overall development of road system in the country.
- Special attention for road development in North–Easte and isolated areas.
- Suggestions for development of urban road system and district and village roads

Target by 2020
1. Primary highway system
   - Expressways—15,766 km
   - National highways—80,000 km

2. Secondary road system
- State highways—1,60,000 km
- Major district roads—3,20,000 km

Rural Road Development Plan

Vision 2025

- Separate document for 20 year period 2005–2025 at the initiative of Ministry of Rural Development is prepared.
- Document targets to provide connectivity to all unconnected habitations in phased manner beyond the norms of PMGSY.

  Phase I: Villages with Population > 1000—to be done by 2003.

  Phase II: Population > 500—to be done by 2007.

  Phase III: Population < 500 (in case of hill states, desert and tribal areas) by 2007.

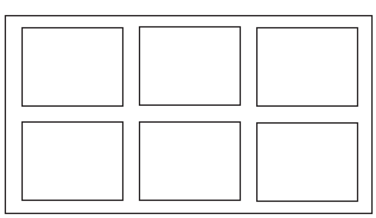
Current Status of Roads

- Expressways—1,208 km
- National highways—92,851 km
- State highways—1,55,716 km
- Major and other district roads—2,577,396 km
- Rural and other roads—1,463,577 km
  Total road network—4.3 million km
- Smallest national highway is NH47—6 km (Thiruvananthapuram to Wellington Island)
- Longest national highway is NH7 (Presently 44)—Varanasi to kanyakumari (2,369 km)

Road Patterns

The choice of a pattern very much depends on the locality, the layout of different towns, villages, industrial and production centres and on choice of planning engineer.

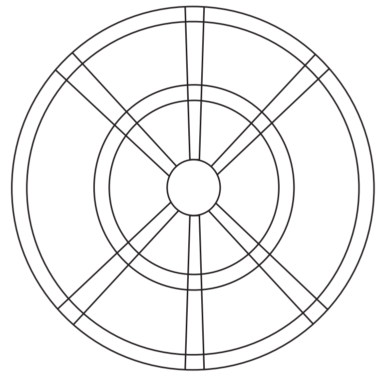
Rectangular or Block Pattern



Rectangular pattern

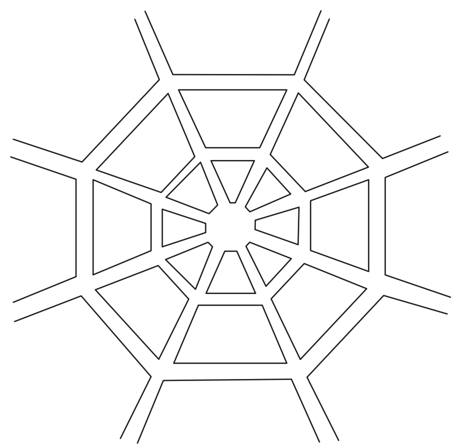
- Used first in Chandigarh (planned city).
- But this is not convenient from traffic operation point of view.

Radial or Star and Circular Pattern



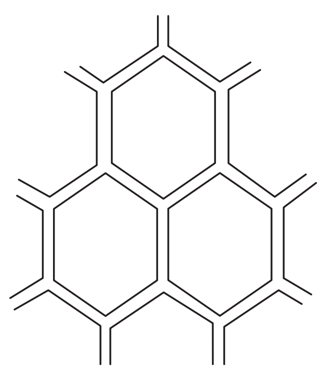
- Used at Connaught place in New Delhi.
- Limitation of this method is congestion of traffic occurs.

Radial or Star and Grid Pattern

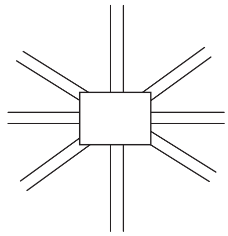


- Used in Nagpur Road plan.
- This method is the most followed one because of better inter communication between each of villages, towns, districts and state capitals.

Hexagonal Pattern



Radial or Star and Block Pattern



Priority of Road Development

- Priority of different roads is calculated to plan out the construction project according to priority in phases.
- Priority is calculated by saturation system or maximum utility system.
- Factors taken into consideration are:
  (a) Population served by road network.
  (b) Productivity served by the network.
    (i) Agricultural products
    (ii) Industrial products

Utility rate of a road

$$= \frac{\sum(\text{Population units} + \text{Production units})}{\text{Road length}}$$

- Villages and settlements may be grouped in population ranges and are assigned utility units.
- Productivity served may be assigned appropriate values of utility units per unit weight.

SOLVED EXAMPLES

Example 1

Three new roads P, Q and R are to be completed in a district during a five year plan period. Using the data given, work out the road with first priority by saturation system. Adopt utility unit of 1 for serving a population range of 2000–5000, or for catering for 1000 tonnes of agricultural products or 100 tonnes of industrial products.

Road	Length (km)	Number of Villages Served Population			Productivity in Thousand (tonnes)	
		<2000	2000–5000	>5000	Agricultural	Industrial
P	20	9	10	5	16	1.5
Q	10	12	2	1	10	0
R	18	20	15	3	21	0.9

Solution

Based on given utilities, the following utilities are taken (approximately)

Population	Utility Unit	
< 2000	0.5	Agricultural products (1000t → 1 unit)
2000–5000	1	Industrial products (1000t → 10 units)
> 5000	2	

Road	Length (km)	Total Utility Units Served by Road	Utility per Unit Length	Priority
P	20	$(9 \times 0.5) + (10 \times 1) + (5 \times 2) + (16 \times 1) + (1.5 \times 10) = 55.5$	$\frac{55.5}{20} = 2.777$	II
Q	10	$(12 \times 0.5) + (2 \times 1) + (1 \times 2) + (10 \times 1) + (0 \times 10) = 20$	$\frac{20}{10} = 2$	III
R	18	$(20 \times 0.5) + (15 \times 1) + (3 \times 2) + (21 \times 1) + (0.9 \times 10) = 61$	$\frac{61}{18} = 3.39$	I

Express Ways

- Yamuna Expressway—165 km in UP.
- Outer Ring Road, Hyderabad—158 km in Telangana.
- Guntur, Vijayawada Expressway—49 km in Andhra Pradesh
- Ahmedabad Vadodara Expressway—95 km in Gujarat
- Mumbai–Pune Expressway—93 km in Maharashtra
- PV Narasimha Rao Express Flyover—11.46 km, Asia's first express flyover in Hyderabad
- Delhi—Noida (Greater Noida) Expressway—Two separate expressways to provide high speed road network. The DND flyway was first expressway built in Delhi.

Highway Alignment and Engineering Surveys

Introduction

The position or the layout of the centre line of the highway on the ground is called the **alignment**. It includes both horizontal and vertical alignments of the roadway.

Basic Requirements of an Ideal Alignment

1. Short
2. Easy
3. Safe
4. Economical

The alignment should be such that it serves maximum population and products (maximum utility).

Factors Controlling Alignment

1. **Obligatory points:**
   (a) Points through which the alignment should pass
   Example: Mountain pass, suitable location of bridge to cross a river, presence of quarry or an intermediate town to be connected.
   (b) Points through which the alignment should not pass.

Example: Religious places, very costly structures, unsuitable land (marshy, peaty or water logged areas)

2. **Traffic:** The new road to be aligned should keep in view the desire lines, anticipated traffic flow, classified traffic volume, their growth and future trends.
3. **Geometric design:** Factors such as sight distance, camber, radius of curve and intersections also govern the alignment of the highway.
4. **Economics:** The alignment should be economical considering the following factors:
   (a) Initial construction cost of road
   (b) Regular and periodic maintenance of road
   (c) Vehicle operation cost
5. **Hill road constraints:**
   (a) Stability of hill slopes
   (b) Drainage of surface and subsurface water
   (c) Resisting length
6. **Other considerations:**

   Drainage, hydrological factors, political considerations and monotony.

Stages of Engineering Surveys for Highway Alignment

1. **Map study/desk study:** With the help of study of topographic maps available from survey of India, various possible alternate routes can be suggested so that further details may be studied later at the site.
2. **Reconnaissance survey:** Site visit and field survey using simple instruments to collect additional details. From these details the proposed alignment may be altered or changed completely.
3. **Preliminary survey:** This is done to collect all the physical information of Longitudinal and cross-sectional profiles, soil survey, drainage and hydrological data, material survey and traffic survey alternate alignment proposed after reconnaissance and finalise the alignment.
   (a) *Conventional approach:* Surveys using the field equipment, taking measurements, collecting topographical data and doing soil survey.
   (b) *Rapid approach:* Aerial photographs and by photogrammetric methods.
   (c) Modern techniques by use of GPS.
4. **Final location and detailed survey:** The centre line of the road finalized in the drawings is to be transferred on to the ground during the location survey. Leveling work for vertical alignment, earthwork calculations, soil survey are all done again to get detailed information.

   This data should be elaborate to prepare plans, designs and estimates of the project.
5. **Maps (drawings):**
   (a) *Key map:* Show proposed and existing roads and places to be connected.
   (b) *Index map:* Show general topography of the area (symbolic representation).
   (c) *Preliminary survey plans:* Details of alternate alignments and information collected in surveying.
   (d) *Detailed plans:* Ground plan with alignment and boundaries, and of existing structures.
   (e) *Longitudinal sections:* Vertical profile of existing ground and proposed road.
   (f) *Detailed cross-sections:* Cross-sections are drawn at every 100 m and should extend upto the proposed right of way. (area of cutting and filling is also shown).
   (g) *Detailed design for cross-drainage and masonry structures.*
   (h) *Land acquisition plans and schedules:* Plans show general details such as buildings, gradients required for assessing the values.
   (i) *Drawings of road intersections:* Details of pavement, shoulders, islands, etc.
   (j) *Land plans for quarries*.

HIGHWAY GEOMETRIC DESIGN

Highway Cross-section Elements

Introduction

Highway cross-section element is a part of geometric design, which include width of pavement, surface characteristics and cross slope. All these elements with factors affecting them and the limiting values for safe and speed transport are discussed.

Geometric design of highways deals with following elements

1. Cross-section elements
2. Sight distance considerations
3. Horizontal alignment details
4. Vertical alignment details
5. Intersection elements

Factors Which Control the Geometric Elements

1. *Design speed:* depends on importance of road and topography. Most important factor in geometric design.
2. Topography
3. *Traffic factors:* Include vehicular and human characteristics.
4. Design hourly volume and capacity.
5. Environmental and other factors.

Highway Cross-section Elements

Pavement Surface Characteristics

1. **Friction (between tyres and the road):**
   - It is one of the factors in determining the operation speed and the minimum distance required for stopping the vehicles.
   - When a vehicle negotiates horizontal curve, lateral friction counteracts centrifugal force and helps in safe operation speed.

Factors affecting friction:

(a) Type, condition and texture of pavement
(b) Type and condition of tyre
(c) Speed of vehicle
(d) Braking efficiency
(e) Load and tyre pressure
(f) Temperature of tyre and pavement

- Coefficient of friction (f) reduces, if pavement surface is smooth and wet >
- f increases with temperature, tyre pressure and load.
- f is more on smooth and worn out tyres on dry pavement because of large area of contact.
- New tyres with good treads are good on wet pavements, because the lubricating effect of water is reduced as the water entrapped between tyre and pavement escapes into tyre treads.
- Higher the speed ⇒ less is the friction

Skid:

- When brakes are applied, the wheels are partially/fully locked.

  ⇒ Then forward movement of vehicle > circumferential movement, which is called skidding.
- Skid occurs on wet (oil/water) pavement.
- If braking efficiency (η_b) is 100% ⇒ skid takes place

  ∴ To avoid skid, $\eta_b < f$.

Slip:

- If revolution of wheels > forward movement of vehicle, it is called slip.
- Slip occurs when vehicle rapidly accelerates from stationary position or from slow speed on pavement which is either slippery and wet or when road surface is loose with mud.

Coefficient of friction (f) as per IRC:

- They have taken worst possible condition to find the f values.

Longitudinal Coefficient of Friction	Lateral Coefficient of Friction
⇒ Wet pavement with retardation of 3.93 m/s^2 is considered f = 0.4 – 0.35 (Low speeds 20-40 km/h) (High speeds 100 km/h)	⇒ Mud on horizontal curves f = 0.15 [For expressways 'f' value is reduced] f = 0.1 (120 km/h speed) = 0.11 (100 km/h speed)

2. **Pavement unevenness:**

   Undulations in pavement results in:
   - Discomfort to road users
   - Increase in fuel consumption and tyre wear
   - Increase in vehicle maintenance cost
   - Reduction in vehicle operating speed
   - Increase in accident rate
   - Unevenness of pavement surface is measured by bump indicator in terms of unevenness index or by roughometer.
   - Sum of vertical undulations along the horizontal stretch expressed as unevenness index (cm/km or mm/km)

     If UI < 150 cm/km ⇒ Comfortable

     = 250 cm/km ⇒ Just satisfactory even at high speeds (100 km/h)

     > 350 cm/km ⇒ Not satisfactory. Causes discomfort even at 50 km/h. Surface has to be relaid.

Causes of Pavement Unevenness

- Improper compaction of pavement layers
- Improper surface and subsurface drainage
- Use of inferior pavement materials
- Poor maintenance

3. **Light reflecting characteristics:**

Light Colored or While Pavement (Concrete)	Black Top Pavement (Bitumen)
Good night visibility	Good day visibility
Cause eye strain due to reflection in day light	Poor night visibility

4. **Cross-slope/camber:** Camber is the transverse slope provided to the pavement surface to drain of rain water. It is provided by raising centre with respect to edges.

   If no camber is provided,

   (a) Water seepage occurs leading to unevenness.
   (b) Stripping of bitumen from aggregates.
   (c) Does not provide dry and skid resistant condition.
   - Required camber of a pavement depends on

(i) Type of pavement surface
- ↗ Flat camber (1.7%–2%) concrete or bituminous concrete
- ↘ Steeper camber for water bound macadam

(ii) Amount of rainfall
- ↗ Flat camber if less rainfall area
- ↘ Steep camber if more rainfall area

- Too steep cross slope is not desirable because of following reasons.
  - (a) Vehicle steering dragged onto one side causing discomfort and more thrust on wheels along pavement edge cause wear of the tyres.
  - (b) Possibility of toppling of slow moving vehicles.
  - (c) Discomfort during overtaking on crossing the crown.
  - (d) Tendency of occupying centre line leading to congestion.
  - (e) Formation of cross ruts due to heavy rains.

IRC recommendations for camber on different roads

Type of Road Surface	Range of Camber in Areas of	
	Heavy Rainfall	Low Rainfall
1. Cement concrete and high type bituminous surface	1 in 50 or 2.0%	1 in 60 or 1.7%
2. Thin bituminous surface	1 in 40 or 2.5%	1 in 50 or 2.0%
3. Water bound macadam and gravel pavement	1 in 33 or 3.0%	1 in 40 or 2.5%
4. Earth road	1 in 25 or 4.0%	1 in 33 or 3.0%

- For expressways (bituminous/cement concrete) camber is

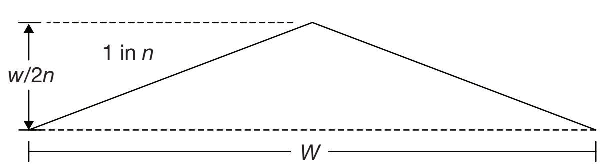
  = 2.5%, if annual rainfall > 1000 mm

  = 2%, if annual rainfall < 1000 mm

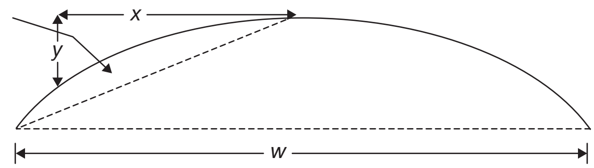
  Camber for shoulder = 0.5% steeper than pavement (maximum –5%, minimum –3%)
- Longitudinal gradient should be as flat as possible for movement of vehicle.
- To satisfy the condition of good drainage and longitudinal gradient

  Longitudinal Gradient = 2 (camber)

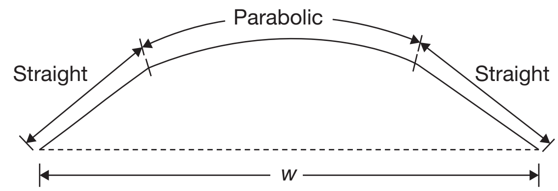
Shape of cross-slope: (1 in $n \Rightarrow$ 1 vertical to n horizontal)
- (a) Straight line—Provided in flat camber (cement concrete) and it is easy to lay.
- (b) Parabolic—Provided in bituminous pavements.
  - Slow moving vehicles, tend to move at centre as they may topple.
  - Overtaking vehicles tend to throw out passengers on crossing camber.
- (c) Straight line and parabolic—This is considered to be the best and overcomes the problems of other shapes.



Straight line camber



Parabolic camber



Straight and parabolic camber

Width of pavement/carriageway: The width of the pavement or carriageway depends on:
- (a) Width of traffic lane which depends on width of vehicle and clearance.
- (b) Number of lanes:
  - Width of vehicle is assumed as 2.44 m and sufficient side clearance of 0.5 m to 0.625 m is adopted.

Class of Road	Width of Carriageway (m)
Single lane	3.75
Double lane without raised herbs	7.0
Double lane with raised herbs	7.5
Intermediate carriage way	5.5
Local streets of residential areas	3
Urban road (not kerbed)	3.5
Urban road (kerbed)	5.5
Expressways (plain and rolling terrain)	3.75
Expressways (mountainous terrain)	3.5
Multi-lane road	3.5 m/lane

Traffic Separators (Medians/Islands)

1. To channelize traffic into streams at intersections.
2. To avoid head on collision of (opposite) moving vehicles.
3. To reduce/avoid glare.
4. To segregate slow traffic and protect pedestrians.

Methods of Providing Traffic Separators

1. Physical dividers
2. Pavement markings
3. Area separators

Width of Medians

- To avoid glare, we need 8–14 m wide medians.

As per IRC → 6 m (minimum)

As per IRC → < 6 m (growing shrubs/trees)

- Rural highways: 5 m and 3 m (if land is restricted)
- Long bridges: 1.2–1.5 m
- If transition (of width) is required: 1 in 15 to 1 in 20 is provided
- Urban area: 1.2 m
- Right turning traffic: 4–7.5 m
- Crossing at grade: 9–12 m
- In urban area,
  - Absolute minimum: 1.2 m
  - Desirable minimum: 5.0 m
- On expressways,
  - Without median barrier: 15 m
  - With median barriers: 4.5 m
- If median has to accommodate structure/pier: 8 m

Kerbs

It is a separator between carriage way and median/shoulder/footpath. They also provide confinement to pavement layers

Types of Kerbs

1. Low mountable: 10 cm high, allow access to vehicles in emergency to mount.
2. Semi barrier type: 15 cm high, only on extreme cases vehicle can mount with difficulty.
3. Barrier type: 20 cm, high and heavy pedestrian traffic built-up areas.
4. Sub-merged kerb: Rural/village roads only for confinement purpose.

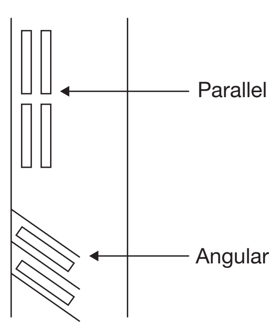
Shoulders

- This act as service lane for vehicles that are disabled.
- Provide structural stability and support to edges of flexible pavement (granular layers).
- Width required is 4.6 m, keeping a side clearance of 1.85 m.

  IRC recommends: 2.5 m (minimum)
- Shoulder should be rough and different coloured to that of pavement.

Parking Lanes

- Parallel parking is recommended as it is safer for moving vehicles. Minimum lane width is 3.0 m.

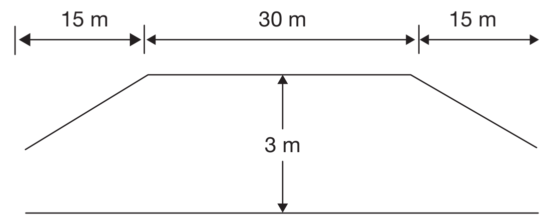


Parallel and angular parking's

Parallel and angular parking's

Truck Lay Byes

- To facilitate rest to drives in long runs.



Truck lay byes

Footpath or Side Walk

- Absolute minimum width is 1.5 m
- Desirable minimum width is 2.0 m

Cycle Track

- Minimum width of 2 m per track and 1 m for every additional track.

Width of road way/width of formation: Total width of [carriage way + shoulder + traffic separator]

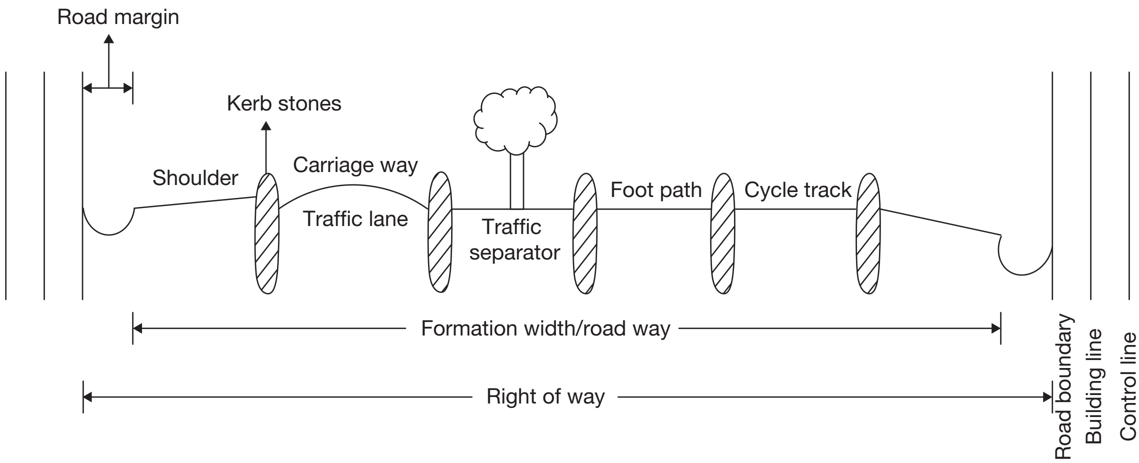
IRC Recommends

Road Classification	Roadway Width (m)	
	Plain and Rolling Terrain	Mountainous and Steep Terrain
1. National and state Highways		
Single lane*	12.0	6.25
Double lane	12.0	8.8
2. Major district roads		
Single lane	9.0	4.75
Double lane	9.0	-
3. Other district roads		
Single lane	7.5	4.75
Double lane	9.0	-
4. Village roads		
Single lane	7.5	4.0

Right of Way and Land Width

- It is the area of land required for the road, along its alignment.
- The width of land acquired for right of way is known as 'land width'.
- Land width is governed by following factors.
  (a) Number of lanes
  (b) Embankment (slope/cutting)
  (c) Drainage considerations
  (d) Visibility features (sight distance)
  (e) Reserve land for future widening

  IRC recommends, 40–65 m road boundary
  80 m—Building lines
  150 m—Control lines



Crosssection of a road

Highway Geometric Design—Gradients

Longitudinal Gradient

- It is the rate of rise or fall along the length of road with respect to horizontal.
- It is expressed as 1 in N (1 vertical to N horizontal).

Types of Gradient

1. **Ruling gradient/design gradient:**
   - This is the gradient usually used for design and it is to be provided throughout the length of road.
   - The grade should be so as to provide uniform operation of vehicle.
   - It should be such that power developed by engine should negotiate resistance to motion on grade at design speeds.
2. **Limiting gradient:**
   - It is steeper than ruling gradient and is provided in small stretches.
   - Provided where gentler slopes would increase the cost (where the topography compels limiting gradient)
3. **Exceptional gradient:** Gradient steeper than limiting gradient and is provided in stretches, such that for 2 km length,

   Rise $\not>$ 100 m (gentler gradient)

   $\not>$ 120 m (steep terrain)

   and $\not>$ 60 m (for 1 km road length)
4. **Minimum gradient (for good drainage requirements):**
   - 0.5% or 1 in 200—Concrete drains.
   - 1% or 1 in 100—Kutcha open drains.
   - For vehicles to move smoothly and for drainage,

   Longitudinal Gradient = 2 (camber)

IRC Recommendations

Terrain Type	Rulling Gradient %	Limiting Gradient %	Exceptional Gradient %
1. Plain and Rolling	3.3	5	6.7
2. Mountainous	5	6	7
3. Steep (over 3000 m above MSL)	6	7	8

Grade Compensation on Curves

- To compensate the loss interactive force on longitudinal gradients when a horizontal curve is encountered, we provide Grade compensation.

  Grade compensation (as per IRC),

$$G = \text{Minimum of} \begin{cases} \dfrac{30+R}{R} \\ \dfrac{75}{R} \end{cases}$$

  R = Radius of horizontal curve in metres.
- As per IRC, Grade Compensation is not necessary for gradients flatter than 4%.
- In applying compensation, the gradients need not be eased beyond 4%.

Example 2

While designing a hill road with a ruling gradient of 6%, if a sharp horizontal curve of 50 m radius is encountered, the compensated gradient at the curve as per the Indian Roads congress specifications should be **[GATE, 2007]**

(A) 4.4% (B) 4.75%
(C) 5.0% (D) 5.25%

Solution

Given R = 50 m
Ruling gradient = 6%

Grade compensation $= \dfrac{30+R}{R}$

$= \dfrac{30+50}{50} = 1.6\%$ (OR)

$= \dfrac{75}{R} = \dfrac{75}{50} = 1.5\%$

Using minimum value, i.e., 1.5%
Hence compensated gradient
= 6 – 1.5%
= 4.5% = 4.4%
Hence, the correct answer is option (A).

Highway Geometric Design—Sight Distances

Introduction

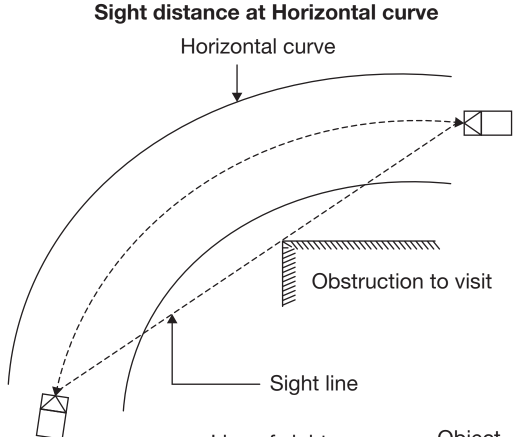
The design of a highway with adequate sight ahead of a travelling vehicle results in safe operation. A knowledge of the sight ahead (road length visible to driver) is needed in designing vertical curves, set back of buildings, slopes and obstructions adjacent to roadway on horizontal curves.

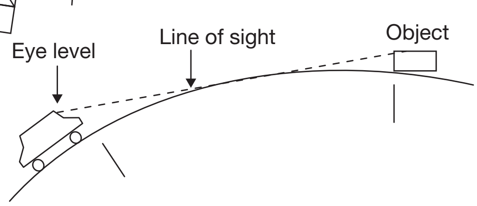
Sight distance is the length of road visible ahead to the driver at any instance.

Restrictions to Sight Distances

1. At horizontal curves, the line of sight is obstructed by objects at the inner side of the curve.
2. At a vertical curve, line of sight is obstructed by road surface.

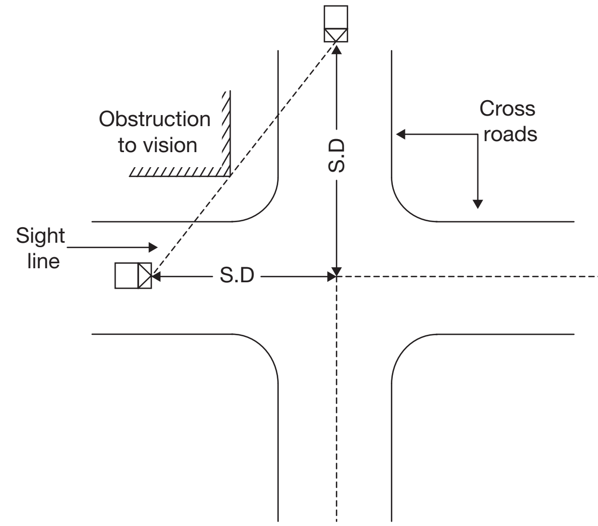
Sight distance at Horizontal curve





Sight distance at Vertical curve

3. At uncontrolled intersection, driver from one approach road able to sight vehicle from other approach.



Sight distance at intersection

- Sight distance required by drivers applies to both geometric design of highways and for traffic control.

Types of Sight Distances

1. Stopping sight distance or absolute minimum sight distance.
2. Safe overtaking sight distance or passing sight distance.
3. Intermediate sight distance.
4. Sight distance at uncontrolled intersections.

Stopping Sight Distance (SSD) Minimum length of road visible to the driver of a vehicle travelling at design speed, to stop the vehicle without collision.

Factors on which SSD Depends

1. Height of drivers eye above road surface (1.2 m)
2. Height of object above road surface (0.15 m)
3. Reaction time of the driver → Braking time / PIEV time
4. Speed of vehicle—Greater the speed, more SSD is required
5. Braking efficiency takes place:
   If $\eta_b = 100\% \Rightarrow$ Skid
   To avoid skidding, $\eta_b < f$.
6. Frictional resistance:
   0.35 (high speeds) – 0.4 (low speed) (longitudinal friction)

PIEV theory

1. **Perception:** Time to perceive an object or situation and to transmit to brain.

2. **Intellection:** Time to understand situation or comparing thoughts.
3. **Emotion:** Time elapsed during emotional sensations and other mental disturbances such as fear, anger, etc.
4. **Volition:** Time taken for final action, i.e., brake application.
   - PIEV time varies from 0.5–4 seconds
   - As per IRC, lag time/PIEV time = 2.5 seconds

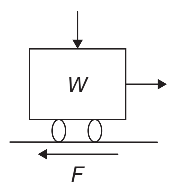
Stopping sight distance = Distance travelled durin lag time (PIEV) + Distance travelled after application of brakes (braking time)

$$\text{SSD} = vt + fWl$$

Frictional resistance = Kinetic energy

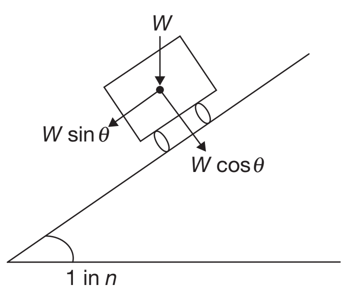
$$fW\,l = \frac{1}{2}\text{mv}^2$$

$$l = \frac{v^2}{2gf} \quad (\because W = \text{mg})$$



- If v in m/s, $\boxed{\text{SSD} = vt + \dfrac{v^2}{2gf}}$
- If V in km/h, $\boxed{\text{SSD} = 0.278Vt + \dfrac{V^2}{254f}}$

SSD on grades:



$$(fW + W\sin\theta) \quad l = \frac{1}{2}mv^2$$

For small angle $\sin\theta \approx \tan\theta \approx \theta$

$$\boxed{\text{SSD} = vt + \frac{v^2}{2g(f \pm n\%)}} \begin{array}{l} +n \text{ for up gradients} \\ -n \text{ for down gradients} \end{array}$$

- If braking efficiency (η) is to be taken care, then

$$\boxed{\text{SSD} = vt + \frac{v^2}{2gf\eta}}$$

- SSD to be provided on single lane road = SSD
- SSD to be provided on two way traffic road = 2(SSD)
- SSD to be provided on divided two way road = SSD
- Minimum sight distance to be provided throughout = SSD

Example 3

A vehicle moving at 60 km/h on an ascending gradient of a highway has to come to stop position to avoid collision with a stationary object. The ratio of lag to brake distance is 6 : 5. Considering total reaction time of the driver as 2.5 seconds and the coefficient of longitudinal friction as 0.36, the value of ascending gradient (%) is ______. **[GATE, 2006]**

(A) 3.3 (B) 4.8
(C) 5.3 (D) 6.8

Solution

$$\frac{S_{\text{log}}}{S_{\text{break}}} = \frac{6}{5} \Rightarrow \frac{vt}{\dfrac{v^2}{2g\left(f + \dfrac{N}{100}\right)}} = \frac{6}{5}$$

$$\frac{t \times 2g\left(f + \dfrac{N}{100}\right)}{v} = \frac{6}{5}$$

$$\frac{2.5 \times 2 \times 9.81\left(0.36 + \dfrac{N}{100}\right)}{\left(60 \times \dfrac{8}{18}\right)} = \frac{6}{5}$$

$N = 4.77$

$\therefore N \approx 4.8\%$

Hence, the correct answer is option (B).

Overtaking Sight Distance (OSD) If the vehicles travel along a road at design speed, theoretically there should be no need for any overtaking.

In case of **mixed traffic conditions**, it is necessary for fast moving vehicle to overtake slow moving vehicle.

- The minimum distance available to the vision of the driver of a vehicle planning to overtake a slow moving vehicle ahead safely without colliding with the vehicles coming in the opposite direction is called **minimum overtaking sight distance**.
- Height of the driver and object are assumed as 1.2 m above road surface.

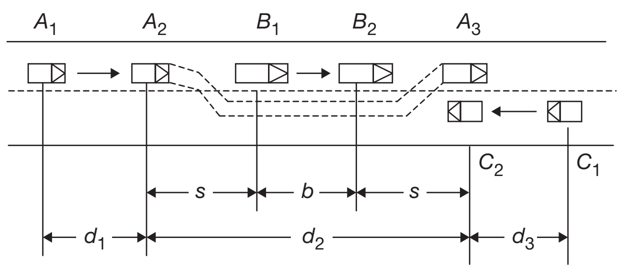
Factors on which overtaking sight distance depends:

1. Height of drivers eye above road surface **(1.2 m)**
2. Height of object above road surface **(1.2 m)**
3. Speed of:
   (a) Overtaking vehicle.
   (b) Overtaken/slow moving vehicle.
   (c) Vehicle coming from opposite direction.
4. Skill and reaction time of driver.
5. Minimum spacing between overtaking and overtaken vehicles.
6. Rate of acceleration of overtaking vehicle.
7. Gradient of the road.

Overtaking process on a two lane highway with two-way traffic movement:

Vehicle A travelling at design speed desires to overtake slower vehicle B moving slowly at v_b m/s or v_b km/h.

Vehicle A has to accelerate, shift to adjacent right side lane, complete the overtaking operation and return to left lane before the vehicle C coming in opposite direction approaches overtaking stretch.



Overtaking operation

1. A reduces the speed to v_B and travels distance d_1 during reaction time of t (as per IRC t = 2 s) from A_1 to A_2.
2. Vehicle A accelerates and overtakes B within a distance d_2 in time T sec from A_2 to A_3 (T is time for overtaking)
3. d_3 is the distance travelled by on coming vehicle in time T sec from C_1 to C_2.
   - As per IRC, reaction time is taken as **2 seconds**

$d_1 = v_b \cdot t$

$d_2 = 2s + b = 2s + v_bT.$

As per IRC, $s = 0.7v_b + l$(l = Length of vehicle)

s: minimum spacing between A_2 and B_1.

$$\boxed{S = (0.7v_b + 6)} \text{ metres.}$$

To Find T Distance travelled by A is,

$$2s + b = v_bT + \frac{1}{2}aT^2.$$

$$2s + v_bT = v_bT + \frac{1}{2}aT^2.$$

$$\boxed{\therefore T = \sqrt{\frac{4S}{a}}}$$

$$= S : m$$

$$a : \text{m/s}^2$$

- If v_b is not given, as per IRC

$$\boxed{\begin{aligned} vb &= (v - 4.5) \\ &= (V - 16) \text{ km/h} \end{aligned}} \quad \begin{aligned} &(\text{here } v \text{ in m/s}) \\ &(V \text{ in km/h}) \end{aligned}$$

- If V in km/h, a in km/h/s

$$\boxed{T = \sqrt{\frac{4 \times 3.6S}{a}}}$$

$$\boxed{T = \sqrt{\frac{14.4S}{a}}}$$

and S = $(0.2V_b + 6)$ in metres

$V_b = (V - 16)$ km/h

- If v, v_b in m/s and T in seconds

$$\boxed{OSD = v_bt + 2S + v_bT + v \cdot T}$$

- If V, V_b in km/h

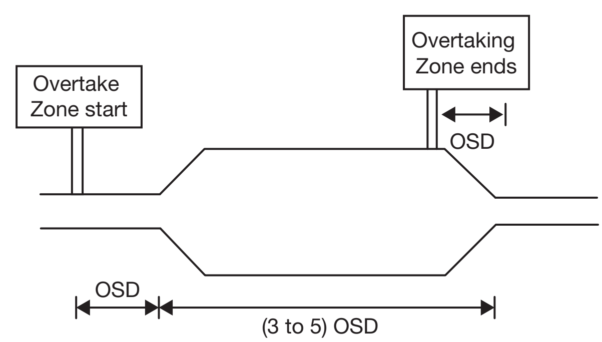
$$\boxed{\text{OSD} = 0.278v_bt + 2S + 0.278\ vb \cdot T + 0.278\ V \cdot T}$$

- On mild gradients (up to ruling gradient on plain and rolling) OSD at both ascending and descending grades are equal to that of level road. At steeper gradients greater than minimum OSD is required
- On roads with two traffic movement, Minimum (OSD = $d_1 + d_2 + d_3$)
- On divided highways and roads having way traffic, (OSD = $d_1 + d_2$)
- On divided highways with four or more lanes, OSD is not required, as no problem of mixed traffic.

  But sight distance should be more than SSD

Length of overtaking zone:

- Minimum length of overtaking zone = 3(OSD)
- Desirable length of overtaking zone = 5(OSD)
- A sign post is to be installed before starting and before ending of overtaking zone at a distance of OSD.



Example 4

For a highway with design speed of 100 km/h, the safe overtaking sight distance is (assume acceleration as 0.53 m/s^2) **[GATE, 1998]**

(A) 300 m (B) 750 m
(C) 320 m (D) 470 m

Solution

$$V = 100 \text{ km/h} \Rightarrow V_b = V - 16$$
$$= 84 \text{ km/h}$$
$$S = (0.2V_b + 6)$$
$$\Rightarrow (0.2 \times 84 + 6) = 22.8 \text{ m}$$
$$a = 0.5 \text{ m/s}^2$$
$$T = \sqrt{\frac{4S}{a}} = \sqrt{\frac{4 \times 22.8}{0.53}} = 13.11 \text{ seconds}$$

Reaction time, $t = 2$ seconds

$$\text{OSD} = d_1 + d_2 + d_3$$
$$= 0.278\, V_b t + (2s + 0.278\, V_b T) + 0.278\, Vt = 757 \text{ m}$$
$$\therefore \text{OSD} \approx 750 \text{ m}$$

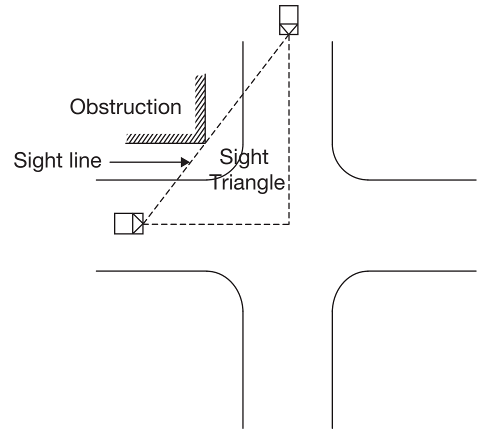
Hence, the correct answer is option (B).

Intermediate Sight Distance At certain stretches of roads where required OSD cannot be provided, intermediate sight distance has to be provided.

$$\boxed{\text{ISD} = 2(\text{SSD})}$$

Sight Distance at Uncontrolled Intersections

- At intersection of roads, there should be a clear view across the corners from a sufficient distance so as to avoid collision of vehicles.
- The design of sight distance at intersections is based on:
  - (a) Enabling the approaching vehicles to change speed ($t = 2$ or 3 seconds as per IRC)
  - (b) Allowing approaching vehicles to stop (SSD)
  - (c) Allow stopped vehicle on minor road to cross the junction.
- For both the approaching vehicles to stop, the sight distance should atleast be equal to SSD on both roads.
- Sight distance requirement of stopping is higher than that of condition (a) above and hence is safe as vehicle can stop if necessary.
- Sight distance available to the stopped vehicle on the minor road should be sufficient to allow the stopped vehicle to start, accelerate and cross the road, before the vehicle on main road reaches intersection at design speed.
- Time required for stopped vehicle to cross the main road without collision depends on:
  - (a) Reaction time of driver
  - (b) Width of main road
  - (c) Acceleration of the vehicle
  - (d) Length of vehicle
- If the sight triangle available is less than the desirable due to unavoidable reasons, sign boards should be put to warn the vehicles to avoid collision.



- IRC recommends minimum visibility distance of 15 m on minor road

On major road:

Visibility Distance	Speed
220 m	100 km/h
180 m	80 km/h
145 m	65 km/h
110 m	50 km/h

Highway Geometric Design—Design of Horizontal Alignment

Introduction

Usually changes in the direction are necessitated in highway alignment due to various reasons such as topographic considerations, obligatory points, etc. Geometric design elements of horizontal alignment of highways should consider safe and comfortable movement of vehicles at the designated design speed. Therefore it is necessary to avoid sudden changes in direction with sharp curves which could not be safely and conveniently negotiated by the vehicles at design speed.

Elements to be Considered in Horizontal Alignment

- Design speed
- Radius of circular curve
- Type and length of transition curves
- Widening of pavement on curves
- Super-elevation
- Set back distance to satisfy sight distance

Design Speed Important geometric details of a highway mainly depend on design speed.

Design speed of roads depend on:

1. Class of the road and
2. Terrain

Two values of design speeds are considered at design stage:

1. **Ruling design speed:** Design of all geometric elements of highway is done for ruling design speed.
2. **Minimum design speed:** This speed is accepted where site conditions or economic considerations are typical.

Road Classification	Design speed in km/h							
	Plain		Rolling		Mountainous		Steep	
	Ruling	Min	Ruling	Min	Ruling	Min	Ruling	Min
Expressways	120	100	100	80	80	60	80	60
NH and SH	100	80	80	65	50	40	40	30

Recommended design speeds for different classes of urban roads are:

1. Arterial roads—80 km/h
2. Sub-arterial roads—60 km/h
3. Collector streets—50 km/h
4. Local streets—30 km/h

Horizontal curves: A horizontal highway curve is a curve in plan to provide change in direction to the centre line of a road.

When a vehicle traverses the horizontal curve, centrifugal force comes into picture which acts horizontally outwards through the centre of gravity of the vehicle, which is resisted by the lateral frictional force between tyres and pavement which enables the vehicle to change the direction along the curve and maintain stability of the vehicle.

Centrifugal force, $P = \dfrac{Wv^2}{gR}$

Where

W = Weight of vehicle (kg)
R = Radius of circular curve (m)
v = Speed of vehicle (m/s)
g = Acceleration due to gravity (9.81 m/s^2)
P = Centrifugal force (kg)

*Centrifugal ratio or impact factor, $\boxed{\dfrac{P}{W}\dfrac{v^2}{gR}}$

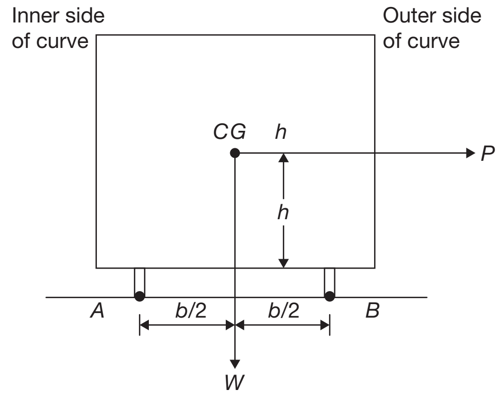
Centrifugal force on a vehicle negotiating the horizontal curve has the following two effects:

1. Overturning of vehicles about the outer wheels.
2. Lateral skidding of vehicle outwards.

1. **Overturning effect:**

h = Height of centre of gravity of vehicle above road surface.

b = Width of vehicle wheel base.



Taking movements about B,

Overturning moment = Restoring moment due to weight due to centrifugal force

$$P \cdot h = \frac{Wb}{2}$$

$$\frac{P}{W} = \frac{b}{2h}$$

- There is a danger of overturning when the centrifugal ratio attains a value of $\dfrac{b}{2h}$
- $\dfrac{P}{W} < \dfrac{b}{2h} \Rightarrow$ Safe from overturning
- $\dfrac{P}{W} \geq \dfrac{b}{2h} \Rightarrow$ Vehicle overturns

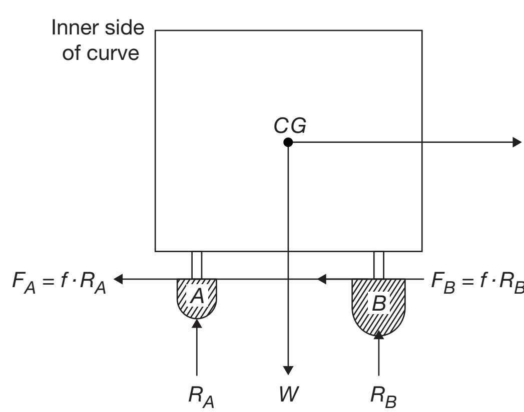
2. **Transverse skidding effect:** If Centrifugal force exceeds the maximum transverse frictional force which is opposite in direction to centrifugal force, the vehicle starts skidding laterally.

P is resisted by F_A and F_B (frictional force)

By equilibrium condition, $\Sigma H = 0$

$$P = F_A + F_B = f(R_A + R_B) = f_W$$

$$\frac{P}{W} = f$$



- Shaded area shows pressure under wheels.

- There is a danger of lateral skidding when the centrifugal ratio attains a value equal to coefficient of lateral friction
- $\frac{P}{W} < f \Rightarrow$ Safe from skidding laterally.
- $\frac{P}{W} \geq f \Rightarrow$ Lateral skidding takes place.
- To avoid both overturning and lateral skidding on horizontal curve, $\frac{P}{W} < \left(\frac{b}{2h} \text{ and } f\right)$
- If $f < \frac{b}{2h} \Rightarrow$ Vehicle would **skid** not overturn.
- If $\frac{b}{2h} < f \Rightarrow$ Vehicle would **overturn** on outer side before skidding.
- When the **limiting equilibrium condition** for overturning occurs, the pressure at the inner wheels becomes equal to zero, as the wheels loose contact with road surface.

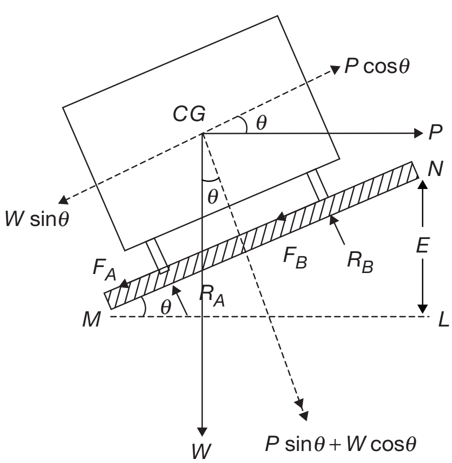
Super-elevation:

- In order to counteract the effect of centrifugal force and to avoid overturning and skidding, the outer edge of the pavement is raised with respect to the inner edge throughout the length of horizontal curve. This process is called provision of super-elevation/cant/banking.

$$e = \frac{\text{NL}}{\text{ML}} = \tan\theta$$

θ is very small, $\tan\theta$ seldom exceeds 0.07

$$e = \tan\theta = \sin\theta = \frac{E}{B}$$



- Total rise of outer edge of pavement

$$\boxed{E = eB}$$

Where, B is width of the pavement.

From the figure, taking equilibrium of the components of forces acting parallel to the inclined plane.

$$P\cos\theta = W\sin\theta + F_A + F_B$$
$$= W\sin\theta + f(R_A + R_B)$$
$$= W\sin\theta + (W\cos\theta + P\sin\theta)$$
$$[\therefore R_A + R_B = P\sin\theta + W\cos\theta]$$
$$P(\cos\theta \quad f\sin\theta) = W(\sin\theta + f\cos\theta)$$

$$\frac{P}{W} = \frac{\tan\theta + f}{1 - f\tan\theta}$$

$f\tan\theta \approx 0.15 \times (0.07) \approx 0.01.$

$\therefore$ Neglecting $f\tan\theta$

$$\frac{v^2}{gR} = \frac{P}{W} = \tan\theta + f = e + f$$

If v in m/s, $\therefore \boxed{e + f = \frac{v^2}{gR}}$

Where

e = Rate of super-elevation = $\tan\theta$
f = Design lateral friction coefficient = 0.15
v = Speed of vehicle, (m/s)
R = Radius of horizontal curve (m)
g = Acceleration due to gravity = 9.81 m/s^2

If V in km/h, $e + f = \frac{(0.278V)^2}{gR}$

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

- Maximum value of e is 0.07 and minimum value of f is 0.15. Therefore the contribution of lateral friction is higher than super-elevation in counteracting centrifugal force and providing stability on horizontal curves.
- At some intersections where super-elevation cannot be provided, allowable speed of vehicle negotiating a turn should be restricted to a condition, as only f resists centrifugal force.

$$f = \frac{v^2}{gR} = \frac{V^2}{127R}$$

Restricted speed without 'e' on horizontal curves,

$$\boxed{V = \sqrt{127\,fR}} \text{ in km/h}$$

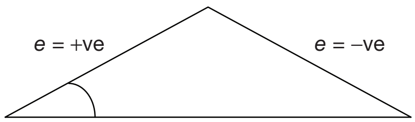
- The super-elevation e on horizontal curve depends on:
  (a) Radius of the curve (R)
  (b) Speed of the vehicle (V)
  (c) Coefficient of lateral friction (f)

Minimum super-elevation:

- To drain off surface water, minimum cross-slope is required.
- When $e \leq$ Camber $\Rightarrow$ Provide camber as minimum 'e'.
- On very flat curves, centrifugal force is less and $e \leq$ Camber $\Rightarrow$ Normal camber is sufficient. But e is

negative for other half of pavement due to normal camber (2 lane, 2 way)

$V = \sqrt{127(f - e)R}$ as e is negative.



- Speed of the road should be limited if it is having negative super-elevation.
- If f lateral $= 0 \Rightarrow e + f = \dfrac{V^2}{127R}$

$$\boxed{\text{Equilibrium 'e'} = \frac{V^2}{127R}}$$

- At equilibrium e, the pressure under outer and inner wheels are equal.

Maximum super-elevation: Maximum values of e are fixed keeping in view mixed traffic conditions (fast and slow traffic), assuming heavily loaded trucks and bullock carts carrying less dense materials to a greater height.

For slow moving vehicle, centrifugal force (P) is less and if super-elevation is high, chances of toppling is high ($\because W > P$)

IRC recommendations:

e_{min} : 0 or negative
e_{max} : 7% plain and rolling terrains.
: 10% steep and mountainous areas.
: 4% urban roads with frequent intersection.

Methods for provision of super-elevation:

1. Elimination of crown
→ Rotating outer half about crown
→ Crown is shifted outwards slowly and thus increasing width of inner half width (Diagonal crown method).

2. Rotation of pavement
→ Rotation about centre line
→ Rotation about inner edge.

Disadvantages by elimination of crown:

- Applied only when e = Camber
- Lot of discomfort during construction.
- Drainage problem during construction on outer edge.

Disadvantages in rotation of pavement:

- Rotation about centre line has drainage problem on inner side.
- If rotated about inner edge, we are disturbing the centre line alignment of pavement.

3. Design of super-elevation:

1. Considering mixed traffic conditions, assuming $f_{lat} = o$, e is calculated for 75% of design speed

$$e = \frac{(0.75v)^2}{gR} \quad \text{where } v \text{ in m/s}$$

$$\boxed{e = \frac{V^2}{225R}} \quad v \text{ in km/h}$$

2. If $e > 0.07$, then assume $e = 0.07$ and find f using

$$e + f = \frac{v^2}{gR} \ (v \text{ in m/s}) \quad \text{(or)}$$

$$e + f = \frac{V^2}{127R} \ (V \text{ in km/h})$$

- If $f \leq 0.15$, provide calculated f value

3. If $f > 0.15$, take $e = 0.07$ and $f = 0.15$ and design speed has to be changed to allowable speed.

- $0.07 + 0.15 = \dfrac{v_a^2}{gR} \Rightarrow v_a = \sqrt{0.22gR}$ m/s

(or)

$$0.07 + 0.15 = \frac{v_a^2}{127R}$$

$$\Rightarrow v_a = \sqrt{27.94R} \text{ km/h.}$$

Example 5

A road is having a horizontal curve of 400 m radius on which a super-elevation of 0.07 is provided. The coefficient of lateral friction mobilized on the curve when a vehicle is travelling at 100 km/h is. **[GATE, 2005]**

(A) 0.007 (B) 0.13
(C) 0.15 (D) 0.4

Solution

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

$$0.07 + f = \frac{\left(100 \times \frac{5}{18}\right)^2}{9.81 \times 400}$$

$$f = 0.13$$

Hence, the correct answer is option (B).

4. Radius of horizontal curve:

- Generally horizontal curves are designed for a particular ruling design speed of highway. But if is not possible, designed for specified minimum design speed.
- Centrifugal force is negotiated by e and f.

$$e + f = \frac{v^2}{gR} = \frac{V^2}{237R}$$

- If design speed is decided for a highway, ruling minimum radius.

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

- If minimum design speed is V km/h, absolute minimum radius

$$R_{\min} = \frac{V'^2}{127(e+f)}$$

$e = 0.07$ for plain and rolling terrains.
$= 0.1$ for hilly terrains.
$f = 0.15$ (coefficient of friction)
$g = 9.81$ m/s^2.

Extra Widening of Pavement on Horizontal Curves

Purpose of Extra Widening of Roads

1. When a vehicle takes a turn on horizontal curve, rear wheels do not follow front wheels which is called as off tracking.
2. At speeds higher than design speeds, e and f are not fully developed and transverse skidding occurs and rare wheels take paths outside of front wheels.
3. Drivers tend to take outer edge for better visibility.
4. Psychological tendency to maintain larger clearance between vehicles (crossing/overtaking)
   - Extra widening

$$W_e = \underset{\substack{\text{(Mechanical}\\ \text{widening for}\\ \text{off tracking)}}}{W_m} + \underset{\substack{\text{(Psychological}\\ \text{Widening)}}}{W_{ps}}$$

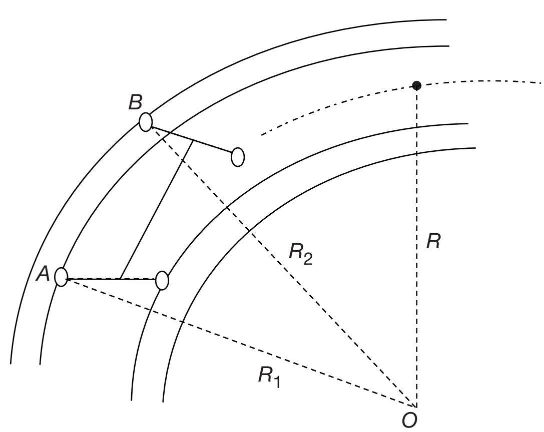
Mechanical Widening

- R = Radius of horizontal curve

R_1 = Radius of outer rear wheel

R_2 = Radius of inner rear wheel

$R_2 - R_1 = W_m \Rightarrow R_1 = R_2 - W_m$ (1)



Off tracking

From triangle OAB,

$$R_2^2 = R_1^2 + l^2$$
$$R_2^2 = (R_2 - W_m)^2 + l^2$$
$$2W_m R_2 - W_m^2 = l^2$$
$$W_m(2R_2 - W_m) = l^2$$
$$W_m = \frac{l^2}{2R} [\because (2R^2 - W_m) \approx 2R]$$

*If there are n lanes, $W_m = \dfrac{nl^2}{2R}$

Psychological Widening (W_{ps})

$$\boxed{W_{ps} = \frac{V}{9.5\sqrt{R}}}$$

$$\therefore \text{ Total widening } \boxed{W_e = \frac{nl^2}{2R} + \frac{V}{9.5\sqrt{R}}}$$

Where
n = Number of traffic lanes
l = Length of wheel base = 6.1 m or 6 m
R = Radius of Horizontal curve (m)
V = Design speed, km/h

- If $R > 300$ m, W_e need not be provided
- If $R > 50$ m, $\dfrac{W_e}{2}$ is provided on both inner and outer side.
- If $R < 50$ m or on sharp hill curves, W_e is provided on inner side only
- If it is a multi-lane pavement, W_e is calculated for $n = 2$ and $\left(\dfrac{W_e}{2}\right)$ is provided for each lane.

Example 6

The extra widening required for a two lane national highway at a horizontal curve of 300 m radius, considering a wheel base of 8 m and a design speed of 100 km/h is **[GATE, 2008]**

(A) 0.42 m (B) 0.62 m
(C) 0.82 m (D) 0.92 m

Solution

$$W_e = W_m + W_{ps}$$
$$= \frac{nl^2}{2R} + \frac{100}{9.5\sqrt{R}}$$
$$= \frac{2(8)^2}{2\times 300} + \frac{100}{9.5\sqrt{300}}$$
$$= 0.82 \text{ m}$$

Hence, the correct answer is option (C).

Setback Distance and Curve Resistance

Introduction

Absolute minimum sight distance that is SSD should be available at every stretch of the highway and even on the horizontal curve sufficient clearance on the inner side of the curve should be provided which is called as setback distance.

Setback Distance (m) or Clearance

It is the distance required from the centre line of horizontal curve to an obstruction on the inner side of the curve to provide adequate sight distance on horizontal curve.

Factors Affecting Setback Distance

1. Required sight distance (SSD, OSD, ISD)
2. Radius of Horizontal curve (R)
3. Length of the curve (L_c)

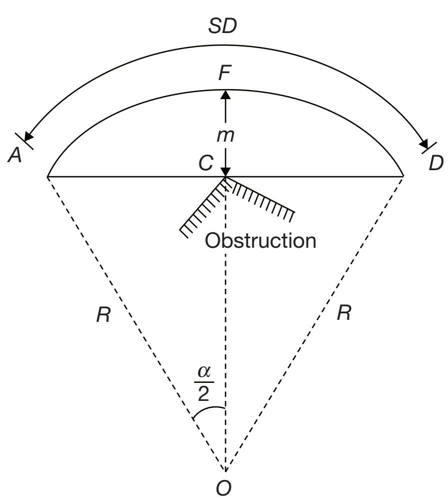
Approximate formula: (From the concept of chords of circle)

Case 1: When $L_c > S$

$$m = \frac{S^2}{8R}$$

Case 2: When $L_c < S$

$$m = \frac{L(2S - L)}{8R}$$



Rational formulae: (As per IRC)

Case 1: $L_c > S$

From above figure $CF = OF - OC$

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

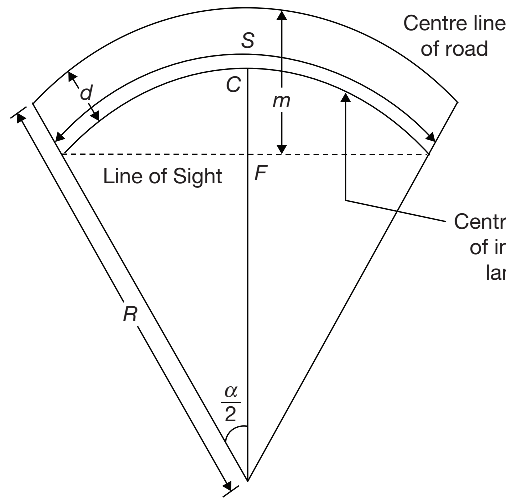
$\alpha = \frac{S}{R}$ radians and $\frac{\alpha}{2} = \frac{180S}{2\prod R}$ degrees.

- For multi-lane roads, sight distance is measured along the middle of the inner side lane.

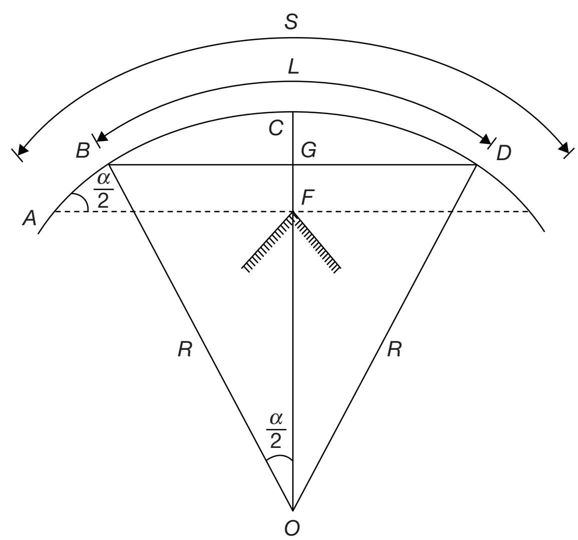
If 'd' is the distance between centre of multilane road and centre of the inner lane,

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

$$\frac{\alpha}{2} = \frac{180S}{2\prod(R - d)} \text{ degrees}$$



Case 2: If $L_c < S$



$$m = OC - OG + FG$$

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

$$\frac{\alpha}{2} = \frac{180L}{2\prod R} \text{ degrees}$$

- For multi-lane roads

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

$$\frac{\alpha}{2} = \frac{180L}{2\prod(R-d)} \text{ degrees.}$$

Example 7

The following data are related to a horizontal curved portion of a two lane highway: length of curve = 200 m, radius of curve = 300 m and width of pavement = 7.5 m. In order to provide a stopping sight distance (SSD) of 80 m, the setback distance (in m) required from the centre line of the inner lane of the pavement is **[GATE, 2012]**

(A) 2.67 m (B) 4.55 m
(C) 7.10 m (D) 7.96 m

Solution

$d = \frac{7.5}{4} = 1.875$ m (centre of road to centre of inner lane $\frac{B}{4}$)

$L_c = 200 \text{ m} > S = 80 \text{ m}$

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

$$\alpha = \frac{180S}{\prod(R-d)} = \frac{180}{\prod(300-1.875)} = 15.38°$$

$$m = 300 - (300 - 1.875)\cos\left(\frac{15.38}{2}\right)$$

$$= 4.56 \text{ m}$$

*But setback distance asked from centre line of inner lane of pavement = $m - d = 4.56 - 1.875 = 2.68$ m

Hence, the correct answer is option (A).

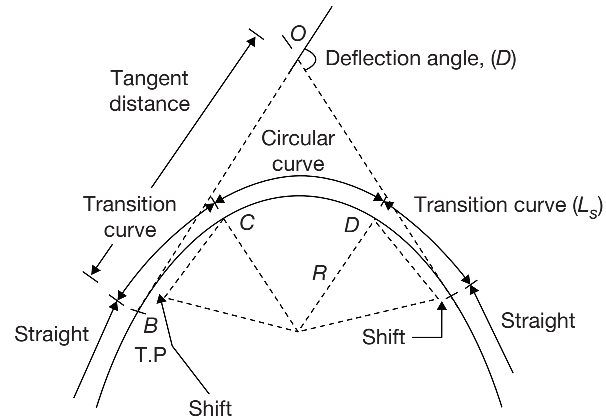
Highway Geometric Design—Transition Curves

Introduction

If a curve of radius R takes off from straight road, centrifugal force suddenly acts on the vehicle just after the tangent point and a sudden jerk is felt on the vehicle. To avoid this a curve having a varying radius which decreases from infinity at the tangent point to a designed radius of the circular curve.

Objectives of Providing Transition Curves

1. To introduce gradually the centrifugal force between the tangent point and the beginning of circular curve for avoiding sudden jerk on the vehicle.
2. To enable the driver to turn the steering gradually for his comfort and safety.
3. To help in gradual introduction of super-elevation and extra width of pavement on circular curve.
4. To improve aesthetic appearance of the road.

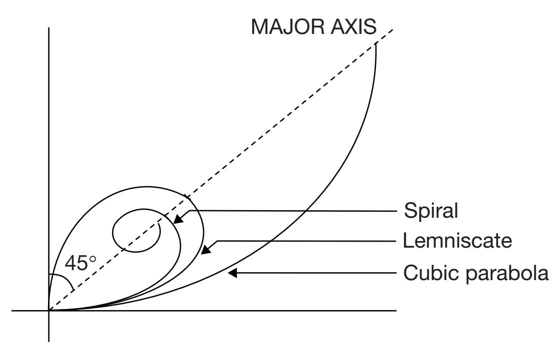


Transition curve in horizontal alignment

- The rate at which the centrifugal force is introduced can be controlled by adopting suitable shape and designing its length.

Types of Transition Curves

1. Spiral
2. Lemniscate
3. Cubic Parabola



Ideal transition curve: The rate of change of centrifugal acceleration is uniform thought the curve.

Upto deflection angle of 4°, all three curves follow same path and practically all curves are same upto 9°.

Spiral (Clothoid/Glovers Spiral)

- Ideal transition curve
- Length of transition curve inversely proportional to radius R of circular curve. i.e., $L_s \propto \frac{1}{R} \Rightarrow L_s R = \text{constant}$
- IRC recommends spiral because
  (a) It satisfies the properties of ideal transition curve.
  (b) Geometric property is such that the calculations and setting out of curve is simple and easy.

- **Equation of spiral:**

  $LR = L_s R_c =$ constant

  $L = m\sqrt{\theta}$

  $m =$ constant $= \sqrt{2RL_s}$

  Where, $\theta =$ tangent deflection angle.

Bernoullie's Lemniscate

- Radius of curve decreases more rapidly with increase in length.
- Mostly used in roads where deflection angle is large.
- It is an autogenous curve (as it follows a path which is actually traced by a vehicle when turning freely).
- The curve is set by polar coordinates.

Cubic Parabola (Froude's Transition/Easement Curve)

- It is set by simple cartesian coordinates.
- It is used for valley curves (as radius reduces very fast with length)
- **Equation:** $y = \dfrac{l^3}{6Rl_S}$

Length of Transition Curve

1. **By rate of change of centrifugal acceleration:**
   - Vehicle travels length L_s of transition curve with uniform speed 'v' m/s in time 't'

     $$\therefore t = \frac{L_s}{v}$$

   - Maximum centrifugal acceleration is attained in time 't'.

     Rate of change of centrifugal acceleration,

     $$C = \frac{v^2}{Rt} = \frac{v^3}{L_s R}\ (\text{m/s}^3)$$

     IRC recommended value of C:

     $C = \dfrac{80}{75 + v}$ m/s^3 (V in km/h) and

     $0.5 < C < 0.8$ m/s^3

2. **By rate of introduction of super-elevation:**
   - e is rate of super-elevation.
   - W is width of pavement.
   - W_e is extra widening provided.
   - B is width of pavement.
   - E is total rise (with respect to inner/centre of road)

     $$E = e \cdot B = e\,(W + W_e)$$

   - Allowing a rate of change of super-elevation of 1 in N

     $L_s = EN = eN(W + W_e)$(E with inner edge)

     $L_s = \dfrac{EN}{2} = \dfrac{eN}{2}\ (W + W_e)$($E$ with respect to centre of road)

     As per IRC:

     $$N \ngtr \begin{cases} 150 - \text{plain and rolling terrains} \\ 100 - \text{built-up areas} \\ 60 - \text{hill roads} \end{cases}$$

3. **By empirical formula:**
   - For plain and rolling terrains:

     $$L_s = \frac{2.7V^2}{R} V \text{ in km/h}$$

   - For mountainous and steep terrain:

     $$L_s = \frac{V}{R} V \text{ in km/h}$$

   (a) The highest length of the curve obtained by all three methods is taken as length of transition curve.

   (b) For expressways, with minimum radius of horizontal curve no transition curves are required.

   For Design speeds

   $$V = \begin{cases} 120 \text{ km/h} \Rightarrow R_{\min} = 4000 \text{ m} \\ 100 \text{ km/h} \Rightarrow R_{\min} = 3000 \text{ m} \end{cases}$$

Shift

The distance between the transition curve at middle and the original circular curve is called shift.

$$\boxed{\text{Shift}, S = \frac{L_s^2}{24R}}$$

Example 8

At a horizontal curve portion of a 4 lane undivided carriageway, a transition curve is to be introduced to attain required super-elevation. The design speed is 60 km/h and radius of the curve is 245 m. Assume length of the wheel base of a longest vehicle as 6 m. Super-elevation rate as 5% and rate of introduction of this super-elevation as 1 in 150. The length of the transition curve (m) required, if the pavement is rotated about inner edge is **[GATE, 2006]**

(A) 81.4 (B) 85.0
(C) 91.5 (D) 110.2

Solution

Width of road $W = 3.5 \times 4 = 14$ m

Extra widening $W_e = \dfrac{nl^2}{2R} + \dfrac{V}{9.5\sqrt{R}}$

$$= \frac{4 \times 6^2}{2 \times 245} + \frac{60}{9.5\sqrt{245}}$$

$W_e = 0.697$ m

If pavement is rotated about inner edge, Length of transition curve

$$m = e\,N\,(W + W_e)$$

$$= \left(\frac{5}{100}\right)(150)(14 + 0.697)$$

$$m = 110.22 \text{ m}$$

Hence, the correct answer is option (D).

Highway Geometric Design—Summit Curves

Introduction

There will be variation in grade in vertical alignment of highway, which cause discomfort to passengers if roads are laid according to that grade. To smoothen out the vertical profile and thus reduce the variation in grades for comfort of passengers. Vertical curves are designed for sight distance and comfort of passengers.

Vertical Curves (Valley Curve)

A valley curve is a curve along the longitudinal profile of the road provided to smoothen out the vertical profile.

1. Summit curves/crest curves with convexity upwards
2. Valley/sag curves with concavity upwards.

Summit Curves

- When a vehicle moves on summit curve, centrifugal force acts upwards against gravity and hence reduces pressure on tyres. Therefore no problem of discomfort.
- Design of summit curves are governed by absolute minimum sight distance as on all highways and no transition curves (for comfort condition) are required.
- Simple parabola is used as summit curve as it gives good riding comfort, simple calculation and uniform rate of change of grade throughout the parabola.

Length of vertical curve:

- Equation of $y = \dfrac{N}{2L}x^2$

  N = difference of grades = $n_1 - n_2$

  Length of curve $L = \dfrac{\text{Total change of grade}}{\text{Rate of change of grade}}$

1. **Length of summit curve (for SSD):** Criteria for design is sight distance.

   Case 1: $L \geq$ SSD (Length of curve = L)

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

   Where

   L = Length of summit curve, m

   S = Stopping sight distance, SSD (m).

   N = Deviation angle, $(n_1 - n_2)$

   H = Height of drivers eye level

   h = Height of object above road surface

   As per IRC: Usually H = 1.2 m and h = 0.15 m

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

   Case 2: When < SSD

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

   As per IRC,

   H = 1.2 m and h = 0.15 m

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

2. **Length of summit Curve for OSD /ISD:**

   Case 1: When $L >$ OSD (or) ISD

   - In OSD, height of object and height of driver are equal $H = h$

$$L = \frac{NS^2}{8H}$$

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

   (as H = 1.2 m as per IRC)

   Case 2: When $L <$ OSD or ISD

$$L = 2S - \frac{8H}{N}$$

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

   (as H = 1.2 m)

   - Minimum radius of parabolic summit curve

$$R = \frac{L}{N}$$

   - On humps, where sight distance is not a problem, simple transition curve is appropriate for comfort riding.

3. **Highest point on the summit curve:** The highest point is at distance of $\dfrac{Ln_1}{N}$ from the tangent point of first grade n_1.

Example 9

Given the sight distance as 120 m. The height of driver's eye as 1.5 m and height of object is 0.15 m. Grade difference of international gradient is 0.09. The required length of summit parabolic curve is **[GATE, 1991]**

(A) 25 m (B) 125 m
(C) 250 m (D) 500 m

Solution

Sight distance $S = 120$ m
Deflection angle $N = 0.09$
Length of summit curve,

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

$$= \frac{0.09 \times 120^2}{(\sqrt{2\times 0.15} + \sqrt{2\times 0.15})^2} = 250 \text{ m}$$

Hence, the correct answer is option (C).

Highway Geometric Design—Valley Curves

Valley curves or sag curves are formed when

1. Descending gradient meets milder descending gradient.
2. Descending gradient meets level gradient.
3. Descending gradient meets ascending gradient
4. Ascending gradient meets steeper ascending gradient

Centrifugal force developed acts downward in addition to self weight and increases pressure on the tyres and causes discomfort topassengers due to impact.

Factors Considered for Designing Valley Curves

1. Comfort to passengers
2. Adequate sight distance for vehicles using head lights at night.
3. Locating lowest point of valley curve for cross drainage.

Cubic parabola is generally preferred in valley curves (as per IRC) and transition curve is used.

There is no problem of overtaking sight distance at night, as opposite vehicles with head lights can be seen from considerable distance.

From Comfort Condition

$$L = 2L_s = 2\left[\frac{Nv^3}{C}\right]^{1/2}$$

Where
v = Design speed m/s
N = Deviation angle in radians
L = Total length of valley curve
C = Allowable rate of change of centrifugal acceleration
$C = 0.6$ m/s^3 is preferred for comfort condition
L_s = Length of transition curve

Minimum radius of valley curve for cubic parabola,

$$R_{\min} = \frac{L_s}{N} = \frac{L}{2N}$$

From Headlight Sight Distance

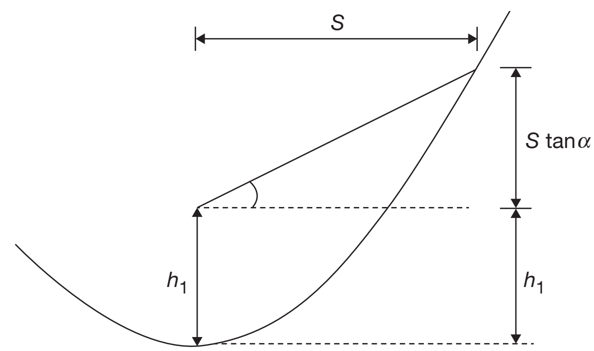
Case 1: $L \geq$ SSD

Sight distance will be minimum when the vehicle is at lowest point on the sag curve

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

$$h_1 + S_{\tan}\alpha = \frac{NS^2}{2L}$$

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



As per IRC:
h_1 = height of head light = 0.75 m
$\mu\alpha$ = Head light beam angle = 1°

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

Case 2: $L <$ SSD

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

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

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

The higher of the above two values is taken as length of valley curve.

Lowest point on valley curve:

- $x = \frac{N_1 L}{N}$

- If valley curve is assumed as cubic parabola

$$X = L\sqrt{N_1 / 2N}$$

Where

X = Location from initial tangent
N_1 = Gradient of initial tangent
N = Deviation angle

Impact factor:

$$I = \frac{\text{Centrifugal force (maximum)}}{\text{Weight of vehicle}}$$

$$I = \frac{P}{W} = \frac{1.6NV^2}{L} \ \% \not< 17\% \text{ (as per IRC)}$$

Example 10

If a descending gradient of 1 in 25 meets an ascending gradient of 1 in 40, then the length of valley curve required for a headlight sight distance of 100 m will be **[IES, 1999]**

(A) 30 m (B) 130 m
(C) 310 m (D) 630 m

Solution

Given SSD = 100 m
From head light sight distance,

Let $L \geq$ SSD

$$L = \frac{NS^2}{1.5 + 0.035S} = \frac{\left(\frac{-1}{25} - \frac{1}{40}\right) \times (100)^2}{(1.5 + 0.035 \times 100)}$$

$L = -130$ m
$\therefore L >$ SSD
$\therefore$ Length of valley curve, $L = 130$ m.
Hence, the correct answer is option (B).

Geometric Design of Railway Track

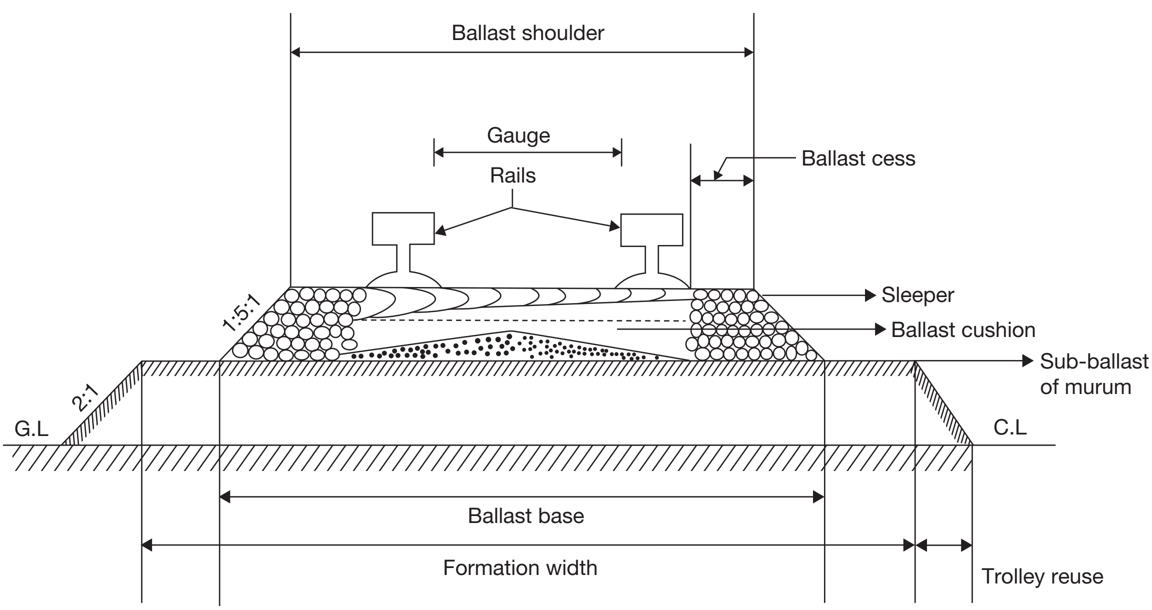
Introduction

Most of the train derailments are due to:

1. Track defects
2. Vehicular defects
3. Operational defects

Civil Engineering is mainly concerned with track defects, and the design aspects of tracks.

Cross-section of a Railway Track



- The combination of rails, fitted on sleepers and resting on ballast and sub-grade is called the railway track. The above figure shows the typical cross-section of a railway track on an embankment.
- The rails are joined in series by fish plates and blots and they are fixed to sleepers by fastenings.
- The sleepers are properly spaced and packed with ballast.
- The layer of ballast rests on the subgrade called the formation width.
- The ballast distributes the load over the formation width and holds the sleepers in position.

- The gauge of a railway track is the clear distance between inner or running faces of two track rails. In India the following types of gauges are used:

Types of Gauge	Gauge Width
Standard gauge (BG)	1.67 m
(or)	
Broad gauge Metre gauge	1.0 m
Narrow gauge (NG)	0.762 m
Light gauge (LG)	0.610 m

Elements of Railway Track

1. Gradients and grade compensation
2. Speed of train
3. Radius or degree of the curve
4. Cant or super-elevation
5. Curves
6. Widening of gauge on curves

Gradients and Grade Compensation

Gradients Gradients are provided on tracks due to following reasons:

1. To provide a uniform rate of rise or fall as far as possible.
2. To reach various stations located at different elevations, and
3. To reduce the cost of earth work.

Ruling Gradient

- This is defined as the gradient which determines the maximum load that the engine can haul on the section.
- It is the maximum gradient allowed on the track section.
  - In plain terrain—1 in 150 to 1 in 200.
  - In hilly regions—1 in 100 to 1 in 150.

Momentum Gradient

- These are the gradients on a section which are severe than ruling gradient but do not determine the maximum load of the train.
- Train while coming down on falling gradient acquires sufficient momentum, which gives kinetic energy to the train which enable it to overcome steeper rising gradient more than ruling gradient for certain length of track.
- Trains should not be stopped in the middle as it loses its momentum. Therefore obstacles like signals should not be provided at momentum gradients.

Pusher/helper Gradient

- In mountainous regions, instead of limiting train load, it may be operationally easy or economical to run train based on load it can carry on remaining track and use of assisting/pusher/banking engine for severe gradient portion. Such gradients are called 'Pusher' or 'Helper' gradients.
- These are important in mountainous terrain where steeper gradients are necessary to reduce the length of the track.

Gradients in Station Yards

- To prevent the movement of standing vehicle on track.
- To prevent additional resistance due to grade on the starting vehicles.
- Maximum gradient = 1 in 400.
  Minimum gradient = 1 in 1000 (for drainage)

Grade Compensation In order to avoid resistances beyond the allowable limits, gradients are reduced on curves, this reduction is called grade compensation for curves.

As per IS specification,

- **For BG:**
  0.04% per degree curve or $\frac{70}{R}$
- **For MG:**
  0.03% per degree curve or $\frac{52.5}{R}$
- **For NG:**
  0.02% per degree curve or $\frac{35}{R}$

Where
BG is broad gauge
MG is Metre gauge
NG is Narrow gauge

Example 11

If the ruling gradient is 1 in 120 on a particular section of broad gauge and at the same time a curve of 4° is situated on this ruling gradient. What should be the allowable ruling gradient?

(A) 1 in 196 (B) 1 in 174
(C) 1 in 163 (D) 1 in 149

Solution

As per IS for BG, grade compensation = 0.04% per degree of curve.

∴ Compensation for 4° curve = 0.04 × 4 = 0.16%.

$$\text{Ruling gradient} = \frac{1}{120}\times 100 = 0.83\%$$

∴ Allowable gradient after compensation,

$= 0.83 - 0.16 = 0.67\%$

$$= \frac{0.67}{100} = 1 \text{in } 149$$

∴ Allowable ruling gradient = 1 in 149.
Hence, the correct answer is option (D).

Speed of the Train

The speed of the train depends upon the strength of the track and the power of the locomotive.

In India maximum speeds achieved by locomotive are:

1. For BG – 96 km/h
2. For MG – 72 km/h
3. For NG – 40 km/h

Safe Speed on Curves Safe speed for all practical purposes means a speed which is safe from the danger of overturning and derailment with certain margin of safety and it depends on:

1. The gauge of track
2. Radius of the curve
3. Distance at which weight of vehicle and its centrifugal force acts from the centre of the track.
4. Amount of super-elevation provided.
5. The presence or absence of transition curves at the ends of the circular curve.

Maximum speed for transition curves as per Indian Railways revised formulae are as given below:

1. **On BG track:**

$$V = \frac{(C_a + C_d)R}{13.76} \text{ (or)}$$

$V = 0.27(C_a + C_d)R.$

Where

V = Maximum speed in km/h

C_a = Actual cant (super-elevation) in mm

C_d = Cant deficiency permitted in mm

R = Radius in metres

2. **On MG track:**

$$V = 0.347\,(C_a + C_d)R$$

3. **On NG track:**

$V = 3.65\sqrt{R - 6}$ subjected to maximum of 50 km/h.

Maximum cant deficiency values for different gauges for Indian Railways are:

(a) BG track—75 mm

(b) MG track—50 mm

(c) NG track—40 mm

Radius and Degree of the Curve

Degree of a curve is also defined as the angle subtended at the centre by a chord of 100 feet 'or' 30.48 m length.

$$D = \frac{1720}{R} \text{ (in Metric units)}$$

- A straight railway track is an ideal condition, but curves are provided to connect important points, avoiding obstructions to have longer and easier gradients.
- Taking into account various effects of curvature, the smallest radius and the largest degree are restricted by
  (a) Wheel base of a vehicle
  (b) Sharpness of the curve

Limit on maximum radii on curves in India:

Maximum degree of curvature:

For BG = 10° (min. R = 175 m)

For MG = 16° (min. R = 109 m)

For NG = 40° (min. R = 44 m)

Relationship between radius and Versine of a curve:

$$V = \frac{C^2}{8R} \text{ m} = \frac{12.5C^2}{R} \text{ cm}$$

Where

V = Versine above the chord length

C = Length of the chord (metres)

R = Radius of circular curve (metres)

Super-elevation or Cant

The aim of providing the super-elevation is to make the force of reaction equal at both the rails and perpendicular to the track and thus equalize the weight on either rail.

The super-elevation aims:

1. To introduce centripetal force to counteract centrifugal force. This prevents derailment and reduce the side wear and creep of rails.
2. To provide equal distribution of wheel loads on two rails so that there is no tendency of track to move out of position.
3. To provide an even and smooth running track to ensure comfortable ride to passengers and safe movement of goods.

Super-elevation,

$$e = \begin{cases} \dfrac{Gv^2}{gR} \text{ m}, v \text{ in m/s} \\ \dfrac{GV^2}{127R} \text{ m}, V \text{ in km/h} \\ \dfrac{GV^2}{1.27R} \text{ cm}, V \text{ in km/h} \end{cases}$$

G = Gange of track.(metres)

For BG = 1.676 m,

MG = 1.0 m

NG = 0.762 m

R = Radius of curve in metres

Equilibrium Cant This is the cant provided when the lateral forces and wheel loads are almost equal. This is provided on the basis of average speed of the trains.

Super-elevation is provided in such a way that:

- The faster trains may travel safely without danger of overturning or discomfort to the passengers.
- Slower trains may run safely without fear of derailment due to excessive super-elevation.

Majority of Indian Railways provide super-elevation for **equilibrium speed or average speed** under average conditions on level track.

1. When maximum allowable speed of section on BG and MG is > 50 km/h

   (a) Average speed $= \frac{3}{4} \times V_{max}$
   (b) Safe speed on curves (by formulae)
   } least of both is average speed

2. When maximum allowable speed of section on BG and MG ≤ 50 km/h

   (a) Average speed $= V_{max}$
   (b) Safe speed of the curve
   } least of both is average speed

3. Weighted average equilibrium/average speed,

$$= \frac{n_1V_1 + n_2V_2 + \cdots}{n_1 + n_2 + \cdots} = \frac{\sum nV}{N}$$

$n_1, n_2, n_3, \ldots$ number of trains running at speeds $V_1, V_2, V_3, \ldots$ respectively and N = Total number of trains on track.

Limit on Super-elevation

- Normally the maximum value of super-elevation is $\frac{1}{10}$ of gauge as per Railway Board.
- Recently, $e_{max} = \left\{\frac{1}{10} \text{ to } \frac{1}{12} \text{ of gauge}\right\}$ as per Railway board.

Cant Deficiency As equilibrium cant is provided for average speed, the super-elevation falls short of that required for fast moving trains. This shortage of cant is called cant deficiency.

Limit on cant deficiency is provided as higher cant deficiency gives rise to higher discomfort to passengers and also higher would be centrifugal force and extra pressure on wheels recommend strong track and fastenings.

Limits on Cant Deficiency

Gange	Cant Deficiency (for Speeds upto 100 km/h) (cm)	Cant Deficiency (for Speeds > 100 km/h) (cm)
BG	7.6	10
MG	5.1	Not Specified
NG	3.8	–

Maximum permissible Speed on a Curve It is the minimum of the below values.

1. **Maximum allowable speed of the section:** Based on track condition and type of traction, standards of signalling and interlocking (authorized by Additional Commissioner of Railways)
2. **Safe speed over the curve:** Calculated by Martin's formula based on equilibrium speed based on actual cant or gauge type.
3. **Speed based on consideration of *e*:** Calculated by formula of equilibrium super-elevation.

   Above three methods are used when length of transition curve can be increased.
4. **Speed from the length of the transition curve:**

   (a) For normal speeds upto 100 km/h

$$V_{max} = \frac{134 \times L}{(e)} \text{ (or) } \frac{134 \times L}{D} \text{ (least of two values)}$$

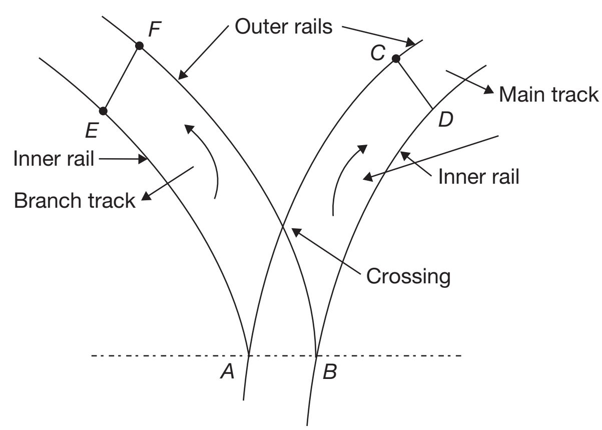
   e = super-elevation, (mm)
   D = Cant deficiency, (mm)

   (b) For high speeds above 100 km/h.

$$V_{max} = \frac{198 \times L}{(e)} \text{(or)} \frac{198}{D} \text{ (least of two values)}$$

   L = Length of transition curve based on rate of change of cant as 38 mm/s for normal speeds and 55 mm/s for high speeds.

Negative Super-elevation



Negative super-elevation

- When the main line is on a curve and has a turnout of contrary flexure leading to a branch line as in the figure the outer rail BF is lower than AE, and this is called negative super-elevation.

- Speeds on both tracks are restricted, particularly on branch line for safe travel.
- Negative super-elevation = (Equilibrium cant − Permissible cant deficiency)

Direction for solved examples 12 and 13:

If a 10° curve track diverges from a main curve of 6° in an opposite direction in the layout of a BG yard. If the maximum speed permitted on the main line is 45 km/h.

Example 12

Calculate the super-elevation required (in cm)

(A) 9.32 (B) 6.91

(C) 6.13 (D) 5.66

Solution

Equilibrium cant for 45 km/h (≤ 50 km/h)

$$e = \frac{GV^2}{1.27R}$$

$$G = 1.676 \text{ m for BG}$$

$$V = 45 \text{ km/h}$$

$$R = \frac{1720}{D}$$

$$= \frac{1720}{6} = 286.67 \text{ m}$$

$$e = \frac{1.676 \times 45^2}{1.27 \times 286.67} = 9.32 \text{ cm}$$

Hence, the correct answer is option (A).

Example 13

Find the speed on the branch line (in km/h)

(A) 40.2 (B) 27.68

(C) 31.23 (D) 26.59

Solution

For BG, cant deficiency for main line = 7.6 cm

∴ Cant for main track = 9.32 − 7.6

= 1.72 cm

∴ Cant to be provided for branch track = −1.72 cm (negative cant)

If cant deficiency permitted = 7.6

Speed of train will be for a cant of = 7.6 + (−1.72) = 5.88 cm

Permissible speed on branch line is calculated as

$$5.88 = \frac{1.676 \times V^2}{1.27 \times 172}$$

$V = 27.68$ km/h

∴ Speed on branch track V

= 27.68 km/h

Hence, the correct answer is option (B).

Curves

- Curves are necessary for a change in alignment or gradient.
- Simple curves are introduced to ease off the changes.
- Curves are used:
  - (a) To bypass any obstacles.
  - (b) To provide easier gradients by diverting from straight route.
  - (c) To join areas with high population.
  - (d) To balance earthwork in excavation (cutting and filling) and hence, reduce cost of construction.

Effects of Curvature

1. There is lateral bending of the rails due to the rigid wheel base of vehicles.
2. There is an extra vertical load on inner or outer rail due to amount of super-elevation and speed of the vehicle.

Types of Curves

1. **Horizontal curves:** Provided when there is change in direction of the alignment of the track. They are usually circular with parabolic transition curves at either end.
2. **Vertical curves:** Provided whenever there is change in the gradient. These are usually parabolic curves.
3. **Simple curves:** It is an arc of a circle designated by the degree or by its radius.
4. **Compound curves:** These are curves composed of two or more simple curves of different radii. These are used to avoid the obstructions like hard roads, deep cuttings, soft grounds, etc.
5. **Parabolic curves:** Exclusively used as vertical curves in railways and highways. These are easily laid by offset method.
6. **Transitional curves:** This is known as easement curve or spiral. These are usually curves of parabolic nature introduced between a straight and a circular curve or between two compound curves.

Objectives of Transition Curve

Primary objective:

1. To decrease radius of curve gradually from infinite to that of circular curve.
2. To attain gradual rise for the desired super-elevation.

Secondary objective:

1. Gradual increase or decrease of centrifugal force provides smooth running of vehicles and comfort of passengers.
2. No sudden application or releasing of the force is encountered.

Requirements of transition Curve

1. It should be perfectly tangential to the straight line.
2. Length of transition curve should be such that curvature may increase at the same rate as the super-elevation.
3. This curve should join the circular arc tangentially.

Type of Transition Curves

1. **Spiral curves:** It is an ideal curve and satisfies all the requirements of a transition curve.

   Rate of change of acceleration is uniform

   Radius of curvature 'α'

   $$= \frac{1}{\text{Length of the curve}}$$

2. **Cubic parabola**
3. **Bernoulli's lemniscate:**
   - In case of railways, a cubic parabola (Fraud's curve) is usually adopted and easily laid by offset method.

$$y = \frac{x^3}{6RL}$$

Where

y = Perpendicular offset of transition at distance x from the commencement of curve

x = Distance of any point on tangent from the commencement of curve

R = Radius of circular curve

L = Total length of transition curve

Length of Transition Curve This length is along the centre line of the track from its meeting point with the straight to that of the circular curve.

- Indian Railways specify greatest of below values as the length of the transition curve.
  (a) $L = 7.2e$
  e = Super-elevation (cms)
  Based on arbitrary gradient (1 in 720)
  (b) $L = 0.073D \times V_{max}$
  Based on rate of change of cant deficiency.
  (c) $L = 0.073e \times V_{max}$
  Based on rate of change of super-elevation.
- Length of transition curve greater of following by another approach.
  (a) As per Railway code,

$$L = 4.4\sqrt{R}$$

Where

R = Radius of curve in metres

L = Length of the curve in metres

(b) At the rate of change of super-elevation of 1 in 360, i.e., 1 cm for every 3.6 m.

(c) Rate of change of cant deficiency, 2.5 cm in not exceeded.

(d) Based on rate of change of radial acceleration, where radial acceleration is 0.3048 m/s^2.

$$L = \frac{3.28v^2}{R} \text{ metres } (v \text{ in m/s}).$$

Vertical Curves

1. Summit curves
2. Sag or valley curves
   - Length of vertical curve depends upon algebraic difference in grades.
   - Rate of change of grade for first class tracks (for maximum speed)
     = 0.1% per 30 m for summit curves
     = 0.05% per 30.5 m for sag curves

Example 14

Find out the length of the curve for a BG curved track having 4° curvature and a cant of 10 cm. The maximum permissible speed on curve is 80 km/h.

(A) 45 m (B) 58 m
(C) 72 m (D) 86 m

Solution

The length of curve will be maximum, out of the following three values.

(i) $L = 7.2 \times e$

$= 7.2 \times 10 = 72$ m (1)

(ii) $L = 0.073 \times D \times V_{max}$

D = Cant deficiency = 7.6 cm (for speeds ≤ 100 km/h)

$L = 0.073 \times 7.6 \times 80 = 44.38$ m (2)

(iii) $L = 0.073 \times e \times V_{max}$

$= 0.03 \times 10 \times 80 = 58.4$ m (3)

Now, length of curve is maximum of Eqs. (1), (2), (3)

$\therefore L = 72$ m

Hence, the correct answer is option (C).

Widening of Gauge on Curves

As the wheel base is rigid, when the outer wheel of the front axle strikes against the outer rail, the outer wheel of the rare axle bears a gap with the outer rail. Therefore provision should be made for this gap, to avoid tilting of rails outward.

- If gauge widening is more than adequate, lateral play of vehicles will be vigorous and sometimes may result in derailment.

Extra width of gauge (d)

$$= \frac{13(B+L)^2}{R} \text{cm} \qquad (1)$$

B = Rigid wheel base (m)
= 6 m (BG)
= 4.88 m (MG)

Where
R = Radius of curve (m)
L = Lap of flange (m)

$$= 0.02\sqrt{h^2 + D \cdot h} \text{ m}$$

h = Depth of wheel flange below rail top level (cm)
D = Diameter of wheel (cm)

Shift The distance by which the circular curve is shifted to a new position is termed as 'shift'.

- For cubic parabola in case of railways,

Shift, $$S = \frac{L^2}{24R} \text{(m)}$$

Where
L = Length of transition curve (m)
R = Radius of circular curve (m)

Example 15

If the wheel base of a vehicle moving on a BG track is 6 m, the diameter of wheel is 1.2 m and depth of flanges below the top of rail is 3.2 cm. Determine the extra width required to be provided on gauge, if the radius of the curve is 150 m.

(A) 2.83 cm (B) 3.55 cm
(C) 4.21 cm (D) 5.64 cm

Solution

h = 3.2 cm
D = 1.2 m = 120 cm
B = 6 m
R = 150 m

Lap of flange

$$L = 0.02\sqrt{h^2 + D \cdot h} \text{ m}$$

$$= 0.02\sqrt{(3.2)^2 + (120 \times 3.2)}$$

$$= 0.397 \text{ m}$$

Extra width of gauge (d)

$$= \frac{13(B+L)^2}{R} = \frac{13(6+0.397)^2}{150}$$

d = 3.55 cm.

Hence, the correct answer is option (B).

Airport Planning and Design

Design of Runway Length

Runway

Runway is defined as the path on which aircraft travels on ground before take-off and landing operations.

- It is usually oriented in the direction of prevailing winds.
- Landing and take-off operations, if done in the opposite direction of wind, shorter runway length is required and if in opposite direction, longer runway length is required.

Cross Wind Component

When wind is blowing at an angle to direction of runway, the normal component of wind is called cross wind component and interrupt the safe landing and take-off of the air crafts.

Permissible limits of cross wind component:

- For small air crafts $\ngtr$ 15 km/h
- For mixed traffic $\ngtr$ 25 km/h
- For big aircrafts $\ngtr$ 35 km/h

Wind Coverage The percentage of time in a year during which the cross wind component remains within the limits as specified above is called wind coverage.

- Runway for mixed traffic is planned for 95% of time in a year.
- For busy airports, wind coverage is increased to 98%–100%.

Wind Rose Diagram

The wind data, i.e., direction, duration and intensity are graphically represented by a diagram called wind rose. The wind data should be collected for a period of atleast 5 years and preferably 10 years.

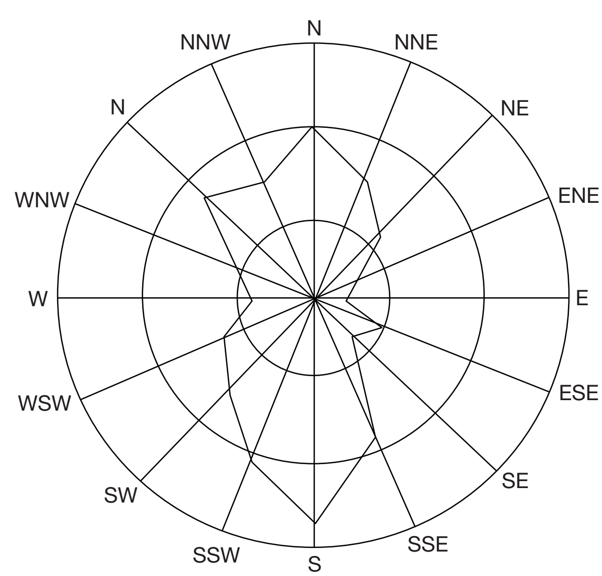
It helps in analyzing the wind data and obtaining the most suitable direction of the runway.

Type I: Showing direction and duration of wind.

Type II: Showing direction, duration and intensity of wind.

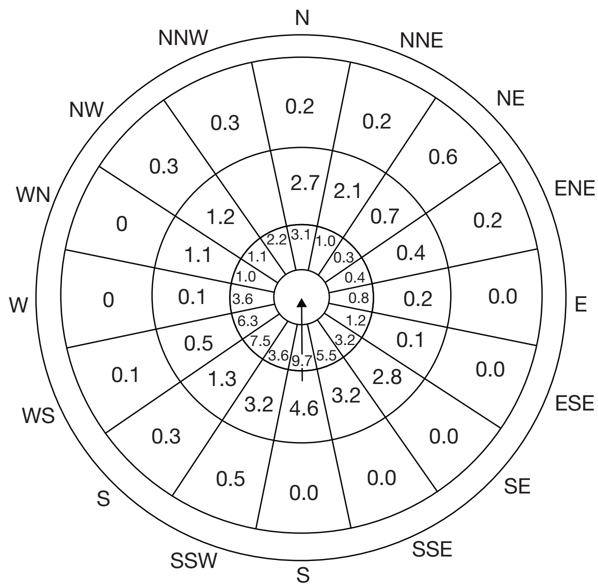
Calm period: The percentage of time during which wind intensity is less than **6.4 km/h.**

Type I wind Rose



Type I: Wind rose diagram

- Radial lines indicate the wind direction and each circle represents the duration of wind.
- Best direction of runway is usually along the direction of the longest line on wind rose diagram.



Type II wind rose

- Each circle represents the wind intensity to some scale. The values entered in each segment represent the percentage of time in a year during which wind having particular intensity, blows from the respective direction.
- Transparent paper strip with three equally spaced lines where spacing is equal to permissible cross wind component is placed on wind rose diagram and rotated.
- It is placed in such a position that the sum of all the values indicating the duration of wind within two outer parallel lines is maximum. Runway should be thus oriented along the direction indicated by the central line.
- Maximum wind coverage = Percentages in segments + Calm period
- If coverage provided by a single runway is not sufficient, two or more number of runways have to be planned such that it gives required coverage.

Change in Direction of Runway

Slight adjustments in the direction are required due to following reasons.

1. **Obstructions:** Obstruction free approaches are required for runway.
2. **Excessive grading:** May need alternative due to excusive grading and earthwork.
3. **Noise nuisance:** To avoid the effect of noise, if the selected runway orientation is along residential areas.

Basic Runway Length It is the length of the runway under the following assumed conditions at the airport.

1. Airport altitude at sea level
2. Temperature at the airport is standard (15°C)
3. Runway levelled in longitudinal direction
4. No wind is blowing on runway
5. Aircraft is loaded to its full capacity
6. There is no wind blowing enroute to the destination
7. Enroute temperature is standard

Basic runway length is determined from following:

1. Normal landing case
2. Normal take off case
3. Engine failure case

Landing case requires that aircraft should come to a stop within 60% of the landing distance.

Take-off requires a clearway, area beyond runway with width of minimum 150 m and is kept free from obstructions.

Any object should not come in the way of plane inclined upward at a slope of 1.25% from runway end.

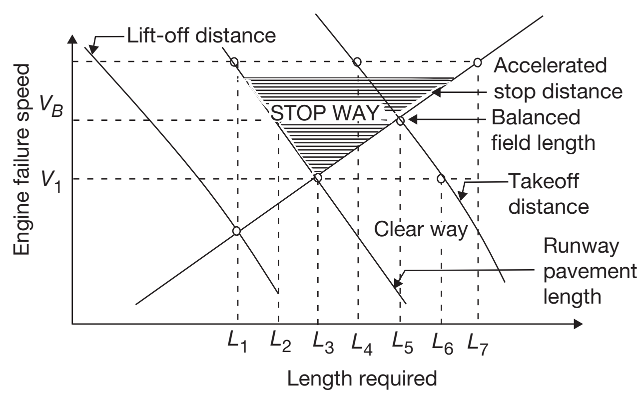
Engine failure case may require either a clearway or stopway or both.

- If engine has failed at a speed < Designated engine failure speed, pilot decelerates the aircraft and makes use of stopway.
- If failed engine speed > Designated engine failure speed, pilot has no option but to take off and take a turn and land again for normal take off.

Piston Engine Aircrafts Full strength pavement is provided for entire take-off distance and the accelerate stop distance.

Designated engine failure speed is so chosen by manufacturer that the distances are equal.

Basic runway length obtained this way is considered to base on balanced field concept and is called balanced runway length. (minimum runway length)



Engine failure case for Jet powered aircrafts

Case 1: Engine failure speed = V_B.

In this lengths of clearway and stopway are equal.

Runway length = L_2

Stop length = $L_5 - L_2$

Clearway length = $L_5 - L_2$

Case 2: Engine failure speed $V_1 < V_B$.
In this lengths of clearway and stopway are equal.
Runway length = L_3
Stop length = 0
Clearway length = $L_6 - L_3$

Case 3: Engine failure speed $V_2 > V_B$.
In this lengths of clearway and stopway are equal.
Runway length = L_1
Stop length = $L_7 - L_1$
Clearway length = $L_4 - L_1$

Corrections for Elevation, Temperature and Gradient

1. **Correction for elevation:** As elevation increases air density reduces, and results in reduction of lift on the wings leading to requirement of longer runway length to acquire great ground speed to rise into the air.
   - ICAO recommends—7% per 300 m rise in elevation above MSL.
2. **Correction for temperature:**
   Airport reference temperature
   $$= T_a + \frac{T_m - T_a}{3}$$
   Where
   T_a = Monthly mean of average daily temperature for hottest month of the year
   T_m = Mean of maximum daily temperature

- Correction = +1% for every 1°C rise of airport reference temperature above standard atmospheric temperature at that elevation (applied after elevation correction)
- The temperature gradient of the standard atmosphere (from the) MSL, to the altitude at which the temperature becomes 15.6°C is = –0.0065°C per metre.
- Temperature gradient = 0 at elevations above the altitude at which temperature is 15.5°C.

3. **Check for total correction for elevation and temperature:** If total Correction for elevation and temperature > 35% (Basic runway length), then corrections should be further checked by conducting specific studies at the site by model tests.
4. **Correction for gradient:**
   - Steeper gradient results in greater consumption of energy and so longer length of runway is required to attain desired ground speed.
   - ICAO does not recommended any specific correction for gradient.
   - FAA recommends increase of runway length at the rate of 20% for every 1% of effective gradient (Correction applied after correcting for elevation and temperature)
   Effective gradient
   $$= \frac{\text{Highest elevation} - \text{Lowest elevation}}{\text{Total runway length}}$$

Direction for solved examples 16 and 17:

The length of the runway under standard conditions is 1840 m. The airport site has an elevation of 250 m. Its reference temperature is 32°C. Assuming all the other conditions to be under standard level.

Example 16

Determine the correction for elevation.
(A) 68 m (B) 83 m
(C) 96 m (D) 107 m

Solution

Correction for elevation

$$= \frac{7}{100} \times 1840 \times \frac{250}{300}$$

Correction = 107.33 m
Correction length = 1840 +107.33
= 1947.33 m
Hence, the correct answer is option (D).

Example 17

Find the correct runway length after applying correction for elevation and temperature.
(A) 1947 m (B) 2062 m
(C) 2268 m (D) 2310 m

Solution

Standard atmospheric temperature at given elevation (250 m)
= 15°C – 0.0065 × 250 = 13.38°C
Correction for temperature:
Rise of temperature = 32 – 13.38 = 18.62°C

$$\text{Correction} = 1947.33 \times \frac{18.62}{100} = 362.59 \text{ m}$$

Corrected length = 1947.33 + 362 .59 = 2310 m
Hence, the correct answer is option (D).

Airport Classification

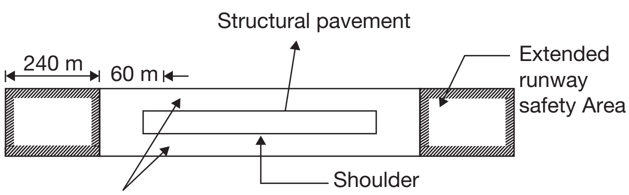
Geometric standards of an airport depend upon:
- Performance characteristics of aircrafts
- Weather conditions
- Services rendered by airport (national/international)

Classification helps in design of airport. International Civil Aviation Organisation (ICAO) classify airports in two ways:

1. Using code letters A to E, A type has longest runway length and E type has the shortest length.
2. In second method, classification is based on equivalent single wheel load (ESWL) and the tyre pressure of the aircrafts (Numbered as 1 to 7).

Runway Geometric Design

1. **Runway length:** Actual runway length is obtained after applying corrections for elevation, temperature and gradient to the basic runway length.
2. **Runway width:**
   - Aircrafts traffic is more concentrated in middle 24 m.
   - Another consideration is outermost machine of large jet aircraft using the airport should not extend off the pavement onto the shoulders, because shoulders are made of loose soil and likely to get into engine and damage it. Outer engine is at 13.5 from longitudinal axis of aircraft.
   - ICAO recommends pavement width as 45 m to 18 m for different types of airports.
3. **Width and length of safety area:** Safety area = Runway + Shoulders + Cleared area



Runway elements

- Width of safety area = Non-instrumental runway,

  A, B, C = 150 m

  D and E = 78 m
- For instrumental runway, it should be minimum 300 m.
- Length of safety area = Length of runway + 120 m
- If stopway is provided, the landing strip should extend to a distance of 60 m beyond the stopway.

4. **Transeverse gradient:**
   - It is for quick drainage of surface water.
   - **Minimum:** As far as possible transverse gradient less than 0.5% should be avoided.
   - **Maximum:** For shoulder, included within 75 m from centre line of runway should prevent ponding but not greater than 2.5%.
   - For remaining portion of shoulder it should not exceed 5%.
   - ICAO recommended

     Maximum {1.5% – A, B, C types; 2% – D and E types}
5. **Longitudinal and effective gradient:**

   The longitudinal gradient of runway increases the required runway length.

   As per ICAO recommendations,
   - For longitudinal gradient:

     A, B, C types of airports = 1.5%

     D and E types of airports = 2%
   - For effective gradient:

     A, B, C types of airports = 1%

     D and E types of airports = 2%
6. **Rate of change of longitudinal gradient:**
   - Abrupt change of longitudinal gradient restricts the height distance and may also cause premature lift-off of the aircraft during the taking off operation.
   - Change of gradients are smoothened by vertical curves.
   - ICAO recommends, rate of change of gradient
     (a) Maximum of 0.1% per 30 m length of vertical curve (A and B types)
     (b) 0.2% for C type
     (c) 0.4% for D and E type
     (d) Vertical curves are not necessary if the change in slope is not more than 0.4%.
7. **Sight distance:**

   As longitudinal gradient is gentle, there would be hardly any sight restriction. But when runways and taxiway intersect each other, there are chances of collision.

   ICAO recommends,
   - Any two points 3 m above the surface of runway should be visible from distance equal to half the runway length. (For A, B, C type.)
   - For any point 3 m and all other points 2.1 m above runway should be visible from distance of atleast half the runway length.

Taxiway Design

Taxiway is a path in an airport connecting runway with ramps, hangars, terminals and other facilities.

Geometric Design Standards

1. **Length of taxiway:**
   - This is as short as possible as it will save fuel.
   - No specifications are recommended.
2. **Width of taxiway:** This is much lower than runway width, because aircraft is not air borne on taxiway and moves with lower speed which makes pilot to drive comfortably on smaller width.
3. **Longitudinal gradient:** As per ICAO recommendations:
   - $\not>$1.5% (A and B type airports)
   - $\not>$ 3% (other type of airports)
4. **Transverse gradient:** (For quick drainage)

   As per ICAO $\not>$ 1.5% (A, B, C type)

   $\not>$ 2% (D and E type)
   - Minimum is not specified, but 0.5% is preferable.
   - FAA recommends – 5% (for first 3 m)
   - 2% (From 3 m)
5. **Rate of change of longitudinal gradient:**
   - ICAO recommends

≯1% per 30 m length of vertical curve B, C type)
≯1.2% per 30 m length of vertical curve (D and E type)

6. **Sight distance:**
   - Smaller value in sufficient on taxiway.
   - ICAO recommends surface of taxiway to be visible.
     (a) from 3 m height for a distance of 300 m (A, B, C type airports)
     (b) from 3 m height for a distance of 250 m (D and E type of airports)
7. **Turning radius:**
   - On a taxiway, if there is any change in direction a curve is so designed that the aircraft can negotiate it without reducing the speed.
   - Circular curve of large radius is suitable for this,

     Radius of $R = \frac{V^2}{125f}$. m curve at taxiway

     Where
     V = Speed (km/h)
     f = Coefficient of friction = 0.13
   - For large subsonic jet transports, R_{min} = 120 m
   - For supersonic transports, R_{min} = 180 m
     Radius of the taxiway by Horonjeff,

$$R = \frac{0.388W^2}{(T/2)-S} \text{ m}$$

Where
T = Width of taxiway pavement (metres)
W = Wheel base of aircraft (metres)
S = Distance between midpoint of main gears and the edge of the taxiway pavement (metres)

Example 18

A taxiway is designed for an airplane which has following characteristics. Determine the turning radius of the taxiway. (airplane is subsonic and assume width of taxiway as 22.5 m)

Wheel base (W) = 18.2 m

Tread of main loading gear = 6.62 m

Turning speed = 35 km/h

Coefficient of friction = 0.13

(A) 66 m (B) 75 m
(C) 120 m (D) 136 m

Solution

(i) Turning Radius $R = \frac{V^2}{125f}$

$$= \frac{(35)^2}{125 \times 0.13} = 75.38 \text{ m} \quad (1)$$

(ii) From Horonjeff's equation,

$$R = \frac{0.388W^2}{\left(\frac{T}{2} - s\right)}$$

$$S = 6 + \frac{6.62}{2} = 9.31 \text{ m and } T = 22.5 \text{ m}$$

$$R = \frac{0.388 \times (18.2^2)}{\left(\frac{22.5}{2}\right) - 9.31} = 66.25 \text{ m} \quad (2)$$

(iii) For subsonic aircraft R_{min} = 120m (3)
Radius of taxiway = 120 m (maximum of Eqs. (1), (2), (3))

Hence, the correct answer is option (C).

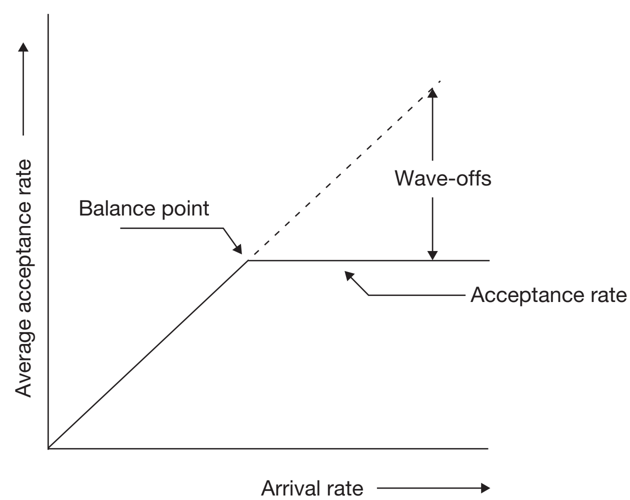
Exit Taxiway

Location of exit taxiway depends on:

1. Number of exit taxiways
2. Exit speed
3. Type of aircrafts
4. Weather conditions
5. Topographical features
6. Pilot variability.

Optimum Location of Exit Taxiways

- Location of exit taxiway should be such that the landing aircraft clears off the runway as early as possible.



Arrival rate and average acceptance rate

- Balance point represents that the runway is loaded to its full capacity. Such a situation is called runway saturation.

Optimum Location For a given set of conditions the exit taxiways should be so located that they yield the highest possible rate of acceptance and is said to be the optimum location.

Design of Exit Taxiway

1. Slightly widened entrance of 30 m gradually tapering to the normal width of taxiway.
2. Total angle of turn of 30° to 45° can be negotiated satisfactorily. Smaller angle is preferable as length of curved path is reduced.
3. High turn-off speeds of 65 to 95 km/h and a compound curve is necessary to minimize the tire wear on the nose gear.
4. For smooth and comfortable turn.

   Turning Radius, $R = \dfrac{V^2}{125f}$ m

   Where
   V = Speed (km/h)
   f = Coefficient of friction = 0.13
5. Length of larger radius curve (of compound curve),

   $$L_1 = \frac{(0.28V)^3}{CR_2}$$

   Where, $C = 0.39$
6. Stopping sight distance, from the edge of runway pavement along the exit taxiway.

   $$SD = \frac{(0.28\,\text{V})^2}{2d}$$

   Where, d = Deceleration in m/s^2. (usually taken as 1 m/s^2)

Example 19

An exit taxiway joining a runway and a parallel main taxiway. The total angle of turn is 30° and turn-off speed is 80 km/h. If the deceleration is 1 m/s^2, find the stopping sight distance?

(A) 165 m (B) 251 m
(C) 310 m (D) 427 m

Solution

$$\text{SD} = \frac{(0.28V)^2}{2d}$$

$$= \frac{(0.28 \times 80)^2}{2 \times 1} = 250.88$$

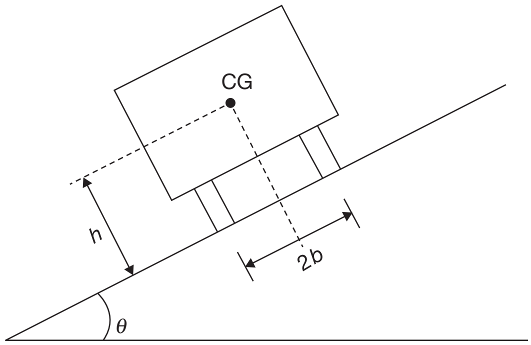
≃ 251 m

Hence, the correct answer is option (B).

Exercises

1. Superior the road
   (A) steeper is the cross slope (or) camber.
   (B) gentler is the camber.
   (C) steeper is the super-elevation.
   (D) lesser is the cost.
2. The value of camber recommended for cement concrete roads in areas of heavy rainfall is _______.
   (A) 1 in 33 (B) 1 in 40
   (C) 1 in 50 (D) 1 in 60
3. The width of carriageway for a single lane is recommended to be
   (A) 7.5 m (B) 7.0 m
   (C) 3.75 m (D) 5.5 m
4. The co-efficient of friction in the longitudinal direction of a highway is estimated as 0.396. The braking distance for a car moving at a speed of 65 km/h is
   (A) 87 m (B) 45 m
   (C) 42 m (D) 40 m
5. A vehicle travelling on dry, levelled pavement at 80 km/h had the brakes applied. The vehicle travelled 76.5 m before stopping. What is the coefficient of friction that has developed?
   (A) 0.2 (B) 0.3
   (C) 0.33 (D) 0.4
6. The safe stopping sight distance for a design speed of 50 km/h for a two lane road with coefficient of friction of 0.37 in m is
   (A) 61.3 (B) 81.7
   (C) 123.7 (D) 161.6
7. A car is moving at a speed of 72 km/h on a road having 2% upward gradient. If the reaction time of the driver is 1.5 seconds, assuming that $f = 0.15$, calculate the distance moved by the vehicle before the car stops finally.
   (A) 24 m (B) 150 m
   (C) 1056 m (D) 324 m
8. The super-elevation needed for a vehicle travelling at a speed of 60 km/h on the curve of radius 128 m on a surface with a coefficient of friction 0.15 is
   (A) 0.71 (B) 0.15
   (C) 0.22 (D) 0.071
9. Design rate of super-elevation for horizontal highway curve of radius 450 m for a mixed traffic condition, having a speed of 125 km/h is
   (A) 1.0 (B) 0.05
   (C) 0.07 (D) 0.154
10. For a road with camber of 30% and the design speed of 80 km/h, the minimum radius of the curve beyond which no super-elevation is needed is
    (A) 1680 m (B) 944 m
    (C) 406 m (D) 280 m
11. There is a horizontal curve of radius 360 m and length 180 m. Calculate the clearance required from the centre line on the inner side of the curve, so as to provide an overtaking sight distance of 250 m.

12. A vehicle is manouvering a horizontal curve of radius R with super-elevation $\theta°$. Find the value of the maximum speed beyond which the vehicle would overturn outward, if $R = 250$ m, $\theta = 5°$, $f = 0.15$, $h = 1$ m, $b = 0.75$ m in (km/h)



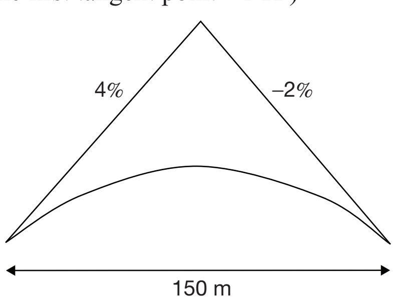
13. Determine the extra width of pavement and the length of transition curve needed on a horizontal alignment of radius 225 m for the two lane road, with a design speed of 80 km/h. Assume the wheel base of design vehicle as 6 m.

14. The ideal form of the curve for the summit curve is
(A) lemniscate (B) parabolic
(C) circular (D) spiral

15. The length of summit curve on a two lane two way highway depends upon
(A) allowable rate of change of centrifugal acceleration.
(B) coefficient of lateral friction.
(C) required stopping sight distance.
(D) required overtaking sight distance.

16. The important factor considered in the design of summit curves on highway is
(A) comfort to passengers.
(B) sight distance.
(C) super-elevation.
(D) impact factor.

17. A parabolic curve is used to connect a 4% upgrade with a 2% down grade as shown in fig. The highest point on the summit is at a distance of (measured horizontally from the first tangent point—FTP)



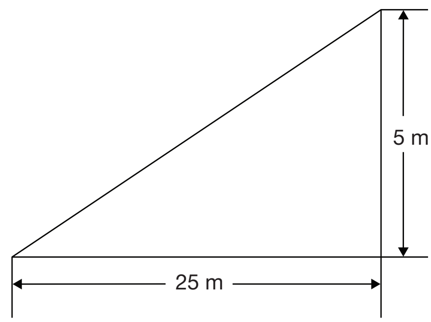
(A) 50 m (B) 60 m
(C) 75 m (D) 100 m

18. An ascending gradient of 1 in 45 meets a descending gradient of 1 in 60. A summit curve has to be designed for design speed of 80 km/h so as to provide a safe overtaking sight distance of 230 m. Estimate the length of the summit curve.

19. The factors affecting the highway alignment are
(A) traffic (B) geometric design
(C) economy (D) All of these

20. A test car of mass 1400 N is travelling at a speed of 85 km/h, when it is suddenly braked the wheels. The average vehicles comes to a stop in a distance of 50 m. Skid resisting force is
(A) 7862 N. (B) 7928 N.
(C) 7804.7 N. (D) 7642 N.

21. The height and width of the pavement are as given in the figure:



If $f = 0.15$ and ruling design speed is 60 km/h. Find the absolute minimum radius on the curve in 'm' is ______.
(A) 8.94 (B) 9.34
(C) 6.62 (D) 7.34

22. The turning angle of the curve is 30° and tractive force on the vehicle is 300 N. Then the loss of tractive force due to turning of vehicle in horizontal curve is
(A) 38 N (B) 40 N
(C) 41 N (D) None of these

23. If width of the vehicle is 6 m and height of the vehicle is 10 m and coefficient of friction 0.15, then
(A) vehicle overturns prior to skidding.
(B) vehicle skids prior to overtaking.
(C) overturning is avoided.
(D) skid is avoided.

24. The design speed of a road is 40 km/h and the radius of curve is 200 m. Then find the length of transition curve for the road of plain and rolling terrain.
(A) 21.6 m (B) 26.1 m
(C) 16.2 m (D) 24.2 m

25. A summit curve is to be designed with two gradients +2% and –6%. The rate of change of gradient is 1% per 100 m length. The minimum radius of curve is
(A) 100 m (B) 1000 m
(C) 200 m (D) 300 m

26. A circular curve of radius 300 m, coefficient of lateral friction of 0.15 and the design speed is 40 km/h. The super-elevation at which equal pressure is distributed on inner and outer wheel would be

(A) 0.02 (B) 0.06
(C) 0.05 (D) 0.04

27. What will be the non passing sight distance on a highway for a design speed of 100 km/h when its ascending gradient is 2%. Assuming coefficient of friction as 0.7 and brake efficiency is 50%.

(A) 176.2 m (B) 174.5 m
(C) 172.3 m (D) 175.05 m

28. A summit curve is formed at the intersection of 3% upgrade and 5% downgrade. What is the length of the summit curve in order to provide a stopping distance of 128 m is

(A) 223 m (B) 248 m
(C) 298 m (D) 300 m

29. Consider following factors:

I. Length of the vehicle
II. Width of the vehicle
III. Approach speed
IV. Stopping time for approaching vehicle
V. Passing sight distance

Which of these factors are taken into consideration for determing yellow time of traffic signal at intersection?

(A) I, II and V (B) II, III and IV
(C) I, III and V (D) I, III and IV

30. The centrifugal ratio of a vehicle is 0.25, width of vehicle is 2.4 m, height of vehicle to its CG is 4.2 m, lateral friction is 0.15, assuming no super-elevation, then

(A) lateral skid occurs first.
(B) overturning occurs first.
(C) neither lateral skid nor overturning.
(D) both lateral skid and overturning occur simultaneously.

31. Find minimum sight distance to avoid head on collision of two cars approaching at 90 km/h and 60 km/h. Given that, reaction time of driver $t = 2.5$ seconds, coefficient of longitude friction $f = 0.7$ and brake efficiency of 50% in either case.

(A) 235.8 m (B) 243.2 m
(C) 256.8 m (D) 292.3 m

32. A road 10 m wide is to deflect through and angle of 65° with the centreline radius 350 m. A transition curve is to be used at each end of a circular curve of such a length that the rate of gain of radial acceleration 0.4 m^3/s, when speed is 60 km/h. Find the shift of the transition curve.

(A) 0.13 m (B) 3.12 m
(C) 0.18 m (D) 3.42 m

33. The slope provided to road surface in the transverse direction to drain the rain water from road surface is called

(A) camber
(B) pavement unevenness
(C) road margins
(D) shoulders

34. Central road fund was created in the year

(A) 1932 (B) 1946
(C) 1929 (D) None of these

35. The Kerb which prevents encroachment by the parking vehicles is known as

(A) semi barrier type kerb.
(B) barrier type kerb.
(C) low kerb.
(D) None of these

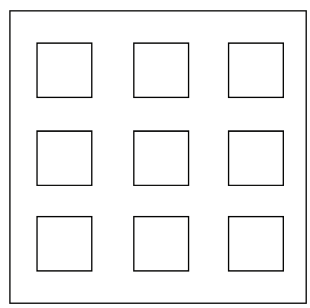
36. The concentration of wheel load at a localized width of pavement can cause

(A) elastic deformation.
(B) plastic deformation.
(C) extra distress.
(D) temperature variation.

37. The longitudinal space separating dual carriage ways is known as

(A) shoulder
(B) curb
(C) median (or) central reserve
(D) carriage width

38.



The above figure represents which type of road pattern?

(A) Hexagonal pattern
(B) Star and grid pattern
(C) Radial (or) block pattern
(D) Star and circular pattern

39. The points controlling the alignment of high ways are known as

(A) alignment points.
(B) obligatory points.
(C) traffic points.
(D) None of these

40. A road is having a horizontal curve of 500 m radius on which a super-elevation of 0.085 is provided. The coefficient of lateral friction mobilized on the curve when a vehicle is traveling at 150 km/h

(A) 0.324 (B) 0.278
(C) 0.562 (D) 0.294

41. Three new roads P, Q, R are planned in a district data for these roads are given in the following table.

Based on the principle of maximum utility the order of priority for these three roads should be

Road	Length	Number of Villages with Population		
		< 200	2000–5000	> 5000
P	22	10	10	5
Q	30	23	15	4
R	14	10	15	2

Codes:
(A) P, Q, R (B) R, Q, P
(C) R, P, Q (D) Q, R, P

42. Match the following:

	List I (Road Classification)		List II (Plain Ruling Gradient)
1.	Express way	**a.**	50
2.	Major district roads	**b.**	100
3.	Village roads	**c.**	50
4.	State of National high ways	**d.**	50

Codes:

	1	2	3	4		1	2	3	4
(A)	a	b	c	d	(B)	d	c	a	b
(C)	c	a	d	b	(D)	c	b	a	d

43. The value of camber recommended for thin bituminous surface in areas of light rainfall is
(A) 1 in 25 (B) 1 in 33
(C) 1 in 40 (D) 1 in 50

44. A horizontal circular curve with a centerline radius of 150 m is provided on a 2–lane, 2–way SH section The width of 2–lane road is 7.0 m. Design speed for this section is 72 km/h. The brake reaction time is 2.5 seconds, and the coefficient of friction in longitudinal and lateral directions are 0.355 and 0.15 respectively. The set back distance from the centre line of inner lane is (considering length of curve > stopping sight distance)
(A) 9.62 m (B) 8.10 m
(C) 7.93 m (D) 9.77 m

45. At a horizontal curve portion of 2 lane undivided carriage way, a transition curve is to be introduced to attain required super-elevation. The design speed is 72 km/h and radius of curve is 150 m. Assume length of wheel base of a longest vehicle as 6.1 m, super-elevation rate as 5% and rate of introduction of this super-elevation as 1 in 150. The length of transition curve (m) required, if the pavement is rotated about inner edge is
(A) 530 m (B) 475 m
(C) 320 m (D) 840 m

46. A valley curve is to be designed for a NH in rolling terrain where a falling gradient of 1 in 20 meets a rising gradient of 1 in 40. The design speed is 80 km/h. To provide safe driving at night the length of valley curve is (Take stopping sight distance as 120 m)
(A) 80 m (B) 150 m
(C) 190.0 m (D) 172.5 m

47. A single lane unidirectional highway has a design speed of 100 km/h. The reaction time of driver is 2.5 seconds and the average length of vehicles is 6.0 m. The coefficient of longitudinal friction of the pavement is 0.4. The capacity of this road is terms of vehicles per hour per lane is
(A) 725 (B) 350
(C) 575 (D) 1020

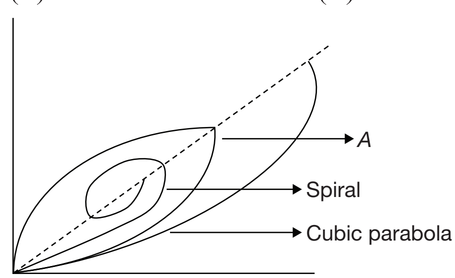
48. From the given data, calculate the length of runway after correction?
Airport elevation = RL 100
Basic length of runway = 600 m
Highest point along the length = RL 98.2
Lowest point along the length = RL 95.2
Temperature correction = 84 m
Note: Apply corrections for elevation, temperature and gradient
(A) 700 m (B) 768 m
(C) 867 m (D) 876 m

49. A 6 degrees curve branches off from a 3 degrees main curve in an opposite direction in the layout of BG yard. If the speed on the branch line is restricted to 35 km/h, what is the speed restriction on the main line. Assume permissible deficiency in cant as 75 mm.
(A) 45.7 km/h (B) 58.2 km/h
(C) 63.9 km/h (D) 75.8 km/h

50. The design value of lateral friction coefficient on highway is
(A) 1.5 (B) 0.5
(C) 0.35 (D) 0.15

51. The radius of horizontal circular curve is 200 m. The design speed is 60 km/h and design coefficient of lateral friction is 0.2. The coefficient of friction needed if no super elevation is provided is
(A) 0.14 (B) 0.16
(C) 0.25 (D) 0.21

52.



A in the above figure is
(A) transition curve.
(B) circular curve.
(C) bernoulli's lemniscates.
(D) None of these

53. While aligning a high way it is necessary to provide a horizontal circular curve of radius 365 m. The design

speed is 85 km/h, length of wheel base is 4 m and width of pavement is 8.5 m. The length of transition curve is
(A) 73.2 (B) 72.3
(C) 27.3 (D) 32.7

54. The wheel base of the vehicle is 8.5 m. The off-tracking while negotiating curved path with mean radius of 32 m is
(A) 1.18 m (B) 1.13 m
(C) 1.12 m (D) 1.15 m

55. A vehicle a of weight 2 tonne skids through a distance equal to 50 m before colliding with other parked vehicle of weight 1 tonne. After collision both the vehicles together skid through a distance of 10 m before stopping. The initial speed of moving vehicle is (Assume coefficient of friction $f = 0.5$)
(A) 9.89 m/s (B) 8.93 m/s
(C) 7.96 m/s (D) 9.82 m/s

56. A vehicle moving at 40 km/h speed was stopped by applying brakes and length of skid mark is 13.2 m. Average skid resistance of pavement is 0.5. The brake efficiency of test vehicle is
(A) 64.6% (B) 73.7%
(C) 86.9% (D) 95.4%

Previous Years' Questions

Direction for questions 1 and 2:

A horizontal circular curve with a centre line radius of 200 m is provided on a 2-lane, 2-way SH section. The width of the 2-lane road is 7.0 m. Design speed for this section is 80 km/h. The brake reaction time is 2.4 s and the coefficients of friction in longitudinal and lateral directions are 0.355 and 0.15, respectively. **[GATE, 2008]**

1. The safe stopping sight distance on the section
(A) 221 m (B) 195 m
(C) 124 m (D) 65 m

2. The set-back distance from the centre line of the inner lane is
(A) 7.93 m (B) 8.1 m
(C) 9.7 m (D) 9.703 m

3. A road is provided with a horizontal circular curve having deflection angle of 55° and centre line radius of 250 m. A transition curve is to be provided at each end of the circular curve of such a length that the rate of gain of radial acceleration is 0.3 m/s^3 at a speed of 50 km per hour. Length of the transition curve required at each of the ends is________. **[GATE, 2008]**
(A) 2.57 m (B) 33.33 m
(C) 35.73 m (D) 1666.67 m

4. A crest vertical curve joins two gradients of +3% and –2% for a design speed of 80 km/h and the corresponding stopping sight distance of 120 m. The height of driver's eye and the object above the road surface are 1.2 m and 0.15 m respectively. The curve length (which is less than stopping sight distance) to be provided is **[GATE, 2009]**
(A) 120 m (B) 152 m
(C) 163 m (D) 240 m

5. The design speed for a two lane road is 80 km/h, when a design vehicle with a wheel base of 6.6 m is negotiating a horizontal curve on that road, the off tracking is measured as 0.096 m. The required widening of carriageway of the two lane road on the curve is approximately **[GATE, 2010]**
(A) 0.55 m (B) 0.65 m
(C) 0.75 m (D) 0.85 m

6. Consider the following statement in the context of geometric design of roads.
I. A simple parabolic curve is an acceptable shape for summit curves.
II. Comfort to passengers is an important consideration in the design of summit curves.
The correct option evaluating the above statements and their relationship is **[GATE, 2010]**
(A) I is true, II is false.
(B) I is true, II is true, and II is correct reason for I.
(C) I is true, II is true, and II is NOT the correct reason for I.
(D) I is false, II is true.

7. A vehicle negotiating a transition curve with uniform speed v. If the radius of the horizontal curve and the allowable jerk are R and J respectively. The minimum length of transition curve is **[GATE, 2011]**
(A) R^3/vJ (B) J^3/Rv
(C) v^3R/J (D) v^3/RJ

Direction for questions 8 and 9:

For a portion of national highway where a descending gradient of 1 in 25, meets with an ascending gradient of 1 in 20, a valley curve needs to be designed for a vehicle travelling at 90 km/h based on the following conditions.
I. Head light sight distance equal to the stopping sight distance (SSD) of a level terrain considering length of valley curve > SSD.
II. Comfort condition with allowable rate of change of centrifugal acceleration = 0.5 m/s^3.

Assume total reaction time = 2.5 seconds
Coefficient of longitudinal friction of the pavement = 0.35.
Height of the head light of the vehicle = 0.75 m and beam angle = 1°. **[GATE, 2013]**

8. What is the length of valley curve (in m) based on the head light sight distance condition?

9. What is the length of valley curve (in m) based on the comfort condition?

10. A road is being designed for a speed of 110 km/h on a horizontal curve with a super-elevation of 8%. If the coefficient of side friction is 0.1, the minimum radius of the curve (in m) required for safe vehicular movement is **[GATE, 2014]**

(A) 115 (B) 152
(C) 264.3 (D) 528.74

11. A super speedway in New Delhi has among the highest super-elevation rates of any track on the Indian Grand Prix circuit. The track requires drivers to negotiate turns with a radius of 335 m and 33° banking. Given this information, the coefficient of side friction required in order to allow a vehicle to travel at 320 km/h along the curve is **[GATE, 2015]**

(A) 1.755 (B) 0.176
(C) 0.253 (D) 2.530

12. The acceleration-time relationship for a vehicle subjected to non-uniform acceleration is:

$$\frac{dv}{dt} = (\alpha - \beta n_0)e^{-\beta t}.$$

Where, v is the speed in m/s, t is the time in seconds, α and β are parameters, and n_0 is the initial speed in m/s. If the accelerating behaviour of a vehicle, whose driver intends to overtake a slow moving vehicle ahead is described as:

$$\frac{dv}{dt} = (\alpha - \beta v)$$

Considering $\alpha = 2$ m/s^2, $\beta = 0.05$ per second and $\frac{dv}{dt} = 1.3$ m/s^2 at $t = 3$ seconds, the distance (in m) travelled by the vehicle in 35 seconds is ______. **[GATE, 2015]**

13. On a circular curve, the rate of super-elevation is e. While negotiating the curve a vehicle comes to a stop. It is seen that the stopped vehicle does not slide inwards (in the radial direction). The coefficient of side friction is f. Which of the following is true? **[GATE, 2015]**

(A) $e \le f$
(B) $f < e < 2f$
(C) $e \ge 2f$
(D) None of these

14. A two lane, one-way road with radius of 50 m is predominantly carrying lorries with wheelbase of 5 m. The speed of lorries is restricted to be between 60 km/h and 80 km/h. The mechanical widening and psychological widening required at 60 km/h are designated as $W_{me,60}$ and $W_{ps,60,}$ respectively. The mechanical widening and psychological widening required at 80 kmph are designated as $W_{me,80}$ and $W_{ps,80,}$ respectively. The correct values of $W_{me,60,}$ $W_{ps,60,}$ $W_{me,80,}$ $W_{ps,80,}$ respectively are **[GATE, 2016]**

(A) 0.89 m, 0.50 m, 1.19 m, and 0.50 m
(B) 0.50 m, 0.89 m, 0.50 m, and 1.19 m
(C) 0.50 m, 1.19 m, 0.50 m, and 0.89 m
(D) 1.19 m, 0.50 m, 0.89 m, and 0.50 m

Answer Keys

Exercises

1. B	**2.** C	**3.** C	**4.** C	**5.** C	**6.** A	**7.** B	**8.** D	**9.** D	**10.** B
11. 19.84 m		**12.** 86.8 km/h		**13.** 0.72 m	**14.** B	**15.** D	**16.** B	**17.** D	
18. 214 m	**19.** D	**20.** C	**21.** A	**22.** B	**23.** B	**24.** A	**25.** A	**26.** B	**27.** D
28. C	**29.** D	**30.** A	**31.** A	**32.** A	**33.** A	**34.** C	**35.** A	**36.** C	**37.** C
38. C	**39.** B	**40.** B	**41.** B	**42.** C	**43.** D	**44.** A	**45.** A	**46.** C	**47.** C
48. C	**49.** C	**50.** D	**51.** A	**52.** C	**53.** B	**54.** C	**55.** A	**56.** D	

Previous Years' Questions

1. C	**2.** D	**3.** C	**4.** C	**5.** C	**6.** A	**7.** D	**8.** 309	**9.** 106	**10.** D
11. A	**12.** 900.79	**13.** A	**14.** B						